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CONTROL OF ZEBRA MUSSEL ATTACHMENT USING ACOUSTICAL MEANS

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ABSTRACT

Laboratory experiments were conducted on the effectiveness of using acoustic energy as a control measure for zebra mussels (*Dreissena polymorpha*) in water handling facilities such as at power plants. Experiments using solid-borne sound at sonic frequencies were effective in preventing attachment of juvenile mussels in a pipe section as compared to a control group. Preliminary indictions are that with further development this could be a practical mitigation strategy against mussels attachment in water handling structures.

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job	file	date	report no.
740627-189-490	825.33, X837.3	April 11, 1991	91-76-K

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EXECUTIVE SUMMARY

Laboratory experiments were conducted on the effectiveness of using acoustic energy as a control measure against zebra mussels *(Dreissena polymorpha)* attachment in water handling facilities such as at power plants. The objective was to explore a non-chemical method for preventing these organisms from settling and blocking water intake systems which can cause plant derating and extra maintenance.

Paired experiments using solid-borne sound at sonic frequencies in the range of 8 to 14 kHz were effective in preventing attachment of juvenile mussels (1 to 5 mm) in a pipe section as compared to a control group. Significant mortality rates were also observed as a result of the exposures. Indications are that the amplitudes of vibration associated with the sound, necessary for preventing attachment or for inducing mortality, are within acceptable limits of structural integrity of water handling facilities.

Further work involving laboratory and field investigations are required to make this method a viable mitigation alternative.

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To: Dr. W.R. Effer
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1.0 INTRODUCTION

An experimental investigation was conducted in the Applied Acoustics Laboratory to determine if it is feasible to prevent zebra mussels (juveniles 1-5 mm) from attaching onto a metallic structure by using acoustic energy. The basic objective is to find means of preventing these organisms from settling and blocking certain water intake systems, such as cooling and service water systems at power stations. Acoustic energy has the potential of providing the desired mitigation effect and at the same time it is relatively benign to the environment /1/.

This investigation was conducted at the request of Dr A.E. Christie of the Environmental Studies and Assessments Department, as part of a program for controlling zebra mussel settling at power stations.

2.0 BACKGROUND

The zebra mussel *(Dreissena polymorpha)* is a recent invader of the Great Lakes. These molluscs have spread from Lake St. Clair where it is believed that they were introduced from Europe in ballast water discharged by ocean freighters. It is expected that they will cause operational problems with Ontario Hydro's generating stations (ie service water and condenser cooling water). Nanticoke TGS became infested with mussels in 1989 and subsequent report of their presence came from Lennox TGS, Lakeview TGS, Lambton TGS, Adam Beck Pumped Storage, and Bruce NPD.

The application of acoustic energy at selected intensities and frequencies, has been explored by others for various marine molluscs with mixed results. Generally there is evidence that sound is detectable by many organisms similar to zebra mussels although little is known about their tolerance to it /1,2/.

3.0 PRELIMINARY TESTS

Scoping acoustical tests were conducted with live samples of mussels (3-12 mm in length, N=10) in order to determine a suitable approach for handling and exposing them to acoustic energy in this investigation.

Using the arrangement shown in Figure 1, the mussels inside a water filled beaker were exposed to sinusoidal tones produced by a high intensity compression driver operating in air. The airborne sounds, transmitted into the beaker, produced levels of up to 170 dB re 1 μPa in the water. The behavioral reaction of the mussels was observed visually as the frequency of the tone was changed every 30 s, in increments of 100 Hz, from 0.2 to 8.0 kHz.

It was observed that at various tones the mussels reacted very quickly with strong contractions resulting in shell closure. Although the mussels remained withdrawn (closed shell) for about 20 h, there appeared to be no other visible sign of trauma compared to a control sample of mussels.

Using the arrangement shown in Figure 2 , a new set of mussels similar to the above was exposed to low frequency, water-borne tones ranging in frequency from 40 to 200 Hz. The mussels were vibrated quite violently by this process for about 5 min during which the sound pressure levels were maintained at about 180 dB re 1 μPa. Although the individuals remained closed during and a few minutes after this exposure, eventually they opened their shells and appeared to be normal as the control group. At this point, however, no other physiological observations were made.

A third experiment was performed by introducing solid-borne sound (sonic vibration) into a short aluminum rod having several zebra mussels voluntarily attached to it. This is shown in Figure 3. Observations made in this experiment indicated that removal of attached mussels from the structure was possible given sufficient exposure to this type of acoustical excitation.

There was also evidence that once the mussels settled, reaction to the stimulus by some individuals was to detach themselves slightly from the surface while still holding by only one (or very few) thread(s). This would have the effect of mechanically isolating the body of the mussel from the vibrating surface thus reducing its exposure.

It was also observed that for some individuals it was not possible to detach themselves from the structure even when exposed to sonic levels where their bodies were forced to rotate around their attachment point due to the structure-fluid vibratory modes that were generated. There was also evidence of mussel mortality due to this exposure.

Based on these observations, the investigation concentrated on the effects produced by introducing solid-borne acoustic energy to a metallic structure as a possible mitigation measure for controlling zebra mussels attachment /3/.

4.0 PROCEDURE

Following is the experimental procedure developed for this phase of the investigation:

4.1 APPARATUS

A section of aluminum piping (Schedule 40 , 55 cm length) was selected as the structure for testing zebra mussel attachment in the presence of acoustic energy. This provided a structure similar in acoustic properties to that of service or industrial water equipment and a convenient medium for handling the mussels. A piezoelectric shaker (5000 Newtons peak force) was bolted to the side of the pipe to provide solid-borne sound in the pipe structure. When submerged in water, this arrangement also produced water-borne sound by direct coupling with the fluid.

The ends of the pipe were partially sealed with a thin plastic sheet to prevent the mussels from migrating or falling out from the pipe while allowing free water exchange. The pipe assembly was suspended to hang horizontally inside a 100 L aquarium tank as shown in Figure 4.

Two additional pipes of the same size and material as the test pipe, were arranged to contain the "control" samples of mussels. Control pipe #1 was installed inside the same tank as the test pipe. Control pipe #2 was installed in a separate identical 100 L tank, in order to avoid transmission of the test sound into the control pipe.

Each tank was filed with approximately 80 L of de-chlorinated water. During the experiments, the positions of the test pipe and control pipe #2 were changed, relative to the water surface, in order to improve observations of mussel attachment. This is illustrated as test arrangements 'A', 'B', and 'C' in Figures 5, 6, and 7 respectively. These changes in pipe position were found to have no significant affect on the experiments in terms of acoustic energy distribution.

The entire equipment was installed inside the anechoic chamber of the Applied Acoustics Laboratory were all the experiments could be conducted under controlled acoustical conditions.

4.2 TEST SAMPLES

Zebra mussels used in all experiments were juvenile and ranged in size from approximately 1 to 5 mm in length. These were collected from Lake Erie, near the shore of Nanticoke TGS, and transported immediately to the Biological Research Laboratory where they were held in controlled environmental chambers, at 4 to 10°C, until needed. Mussels were acclimated to room temperature before use.

Unlike veligers, juvenile zebra mussels are not planktonic but are very mobile and capable of attaching onto solid surfaces as well as clumping on top of each other. These mussels can also float or be carried in fast flowing water and easily find their way into water intake equipment. The premise in this investigation was that if attachment of mussels at this stage could be controlled, then it would prevent a build up of larger size mussels from settling in such equipment.

For each experiment, three batches of approximately 100 mussels were hand picked, inspected for health status and brought to the acoustics laboratory for use. Only live healthy mussels were included in these experiments. Each batch of 100 mussels was immediately inserted into each of the three pipes and the acoustical test was started. The large number of mussels was necessary to minimize expected variability in observations due to mussel distribution and behaviour.

4.3 METHOD

A total of twenty-nine paired experiments were performed in this investigation at selected frequency ranges and amplitudes of acoustical excitation. Paired experiments involved observations made in the test pipe and in the control pipe #2 (Figure 5). Observations made from control pipe #1 were used only as complementary information on the state of health of the mussels during experimental periods. This batch could not be used for attachment observations because they were affected by the water-borne sound transmitted from the test pipe in the same tank.

The shaker in the test pipe was set to generate sinusoidal oscillations sweeping continuously over a frequency range of 1500 Hz every 10 s. Duration of exposures were aimed to be about 24 h but were varied depending on the results being observed at the time. In some of the most promising experiments, in terms of positive results, replicates were made using a wider range of 2000 Hz. The drive frequencies used in these experiments started at 3 kHz and ended at 18 kHz. This was within the normal frequency response of the shaker.

The drive level into the shaker was set to be constant at either 10, 25, or 50 percent of full power throughout each experiment. An accelerometer mounted at an arbitrary fixed location on the pipe, monitored the vibrational amplitude of the pipe in terms of RMS acceleration units in "g's"*. As expected the pipe response was variable due to the multitude of vibrational modes generated by the structural dynamics of the pipe. The mean acceleration of vibration in these experiments was found to be between 30 and 350 g's.

The state of attachment of the mussels in each pipe was classified simply as either "attached" or " unattached". This was done by gently spilling out the water and unattached mussels from the pipe while removing it from the tank. Any mussels still holding to the pipe were counted as "attached". The distribution of mussels within the control pipes was used as an indicator of their well-being and for comparison with the test. In the absence of the acoustical exposure, about 90 percent of a healthy batch of mussels would normally attach and migrate inside the pipe surface within a few minutes of insertion. A typical distribution of mussels in a control group is shown in Figure 8.

Assessments of mortality was made for all individuals (attached or not) immediately after each experiment ended. This was determined by behavioral probing and by direct observation using a dissecting microscope (20-50 x magnification).

5.0 RESULTS AND DISCUSSION

The pattern of mussel attachment inside the test and control pipes was established during the initial hour from start of each experiment. In those cases which ultimately resulted in total unattachment, the results could be observed within the first few minutes. The input parameters, measured structural responses of the test pipe, and a summary of the biological observations corresponding to each of the twenty-nine experiments are presented in Appendix A, Figures A1 to A29.

Effective prevention of zebra mussel attachment was observed at various sonic frequencies in the range of 8 to 14 kHz when the structural vibration of the pipe exceeded a certain minimum value. In this case the mean acceleration of the pipe surface was in excess of 70 g' at 8 kHz and 150 g' at 14 kHz. A summary of the effectiveness of the various exposures presented is shown in Figure 9.

---

*The unit "g RMS" refers to the root-mean-square where $g = 9.8\ m/s^2$.

A breakdown of the results in three of the frequency ranges used, in terms of amplitude (ie mean acceleration) and percent unattached or dead, are illustrated in Figures 10, 11, and 12:

In the 8 to 10 kHz range (Figure 10) nearly 100 percent unattachment was achieved with vibration amplitudes up to about 150 g'. Mortality in this frequency and amplitude range was 75 to 95 percent.

In the 10 to 12 kHz range (Figure 11) virtually 100 percent unattachment was achieved with vibration amplitudes exceeding about 200 g. With the exception of one test, the mortality rates in this case were also nearly 100 percent.

Finally, in the 12 to 14 kHz range (Figure 12) about 90 percent unattachment was recorded with amplitudes of about 210 g'. Mortality was around 70 percent. Higher amplitudes in this frequency range may have yielded better results but could not be attempted at this time.

An analysis of the variance on the above results suggests that amplitude was more significant than frequency in affecting mussel unattachment (Table 1). These factors, however, were not as clear in the mortality observations (Table 2). The data for this analysis are in Appendix B.

TABLE 1

ANALYSIS OF VARIANCE COMPARISON OF THE NUMBER OF UNATTACHED AS A FUNCTION OF FREQUENCY AND AMPLITUDE

Comparison	Variable	Degree of Freedom	F-statistic	Probability
Control	amplitude	1,19	0.18	0.85
	frequency	1,19	0.61	0.55
Experiment	amplitude	1,19	3.20	0.005*
	frequency	1,19	1.56	0.13

*significant effect $P<0.05$

TABLE 2

ANALYSIS OF VARIANCE COMPARISON OF ZEBRA MUSSEL MORTALITY AS A FUNCTION OF FREQUENCY AND AMPLITUDE

Comparison	Variable	Degree of Freedom	F-statistic	Probability
Control	amplitude	1,19	1,76	0.09
	frequency	1,19	0.66	0.51
Experiment	amplitude	1,19	3.07	0.007*
	frequency	1,19	2.67	0.02*

*significant effect $P<0.05$

In cases were the vibration of the structure was moderate, significant "clumping " was observed with occasional individuals holding by a few threads and a number of others attaching onto their shell. At higher vibration levels, mean acceleration exceeding about 100 g', zebra mussels were found to be "skidding" on the inside surface without any control of their own. In such cases there were a significant number of mortalities, many with almost total disintegration of soft body parts and shells. An example of this is illustrated in Figure 13.

A significant amount of collateral unattachment was found to occur with the mussel batches placed in the second pipe within the test tank (ie control pipe #1). These were observed to be affected by acoustic energy transmitted by water-borne coupling between the two closely spaced (10 cm) pipes. Observations made in this second pipe is included with all data which are listed in Appendix C.

It is important of course, that the acoustic energy necessary for preventing mussel attachment does not result in vibration levels that would damage equipment structures. Acceptable vibration limits generally increase with frequency and depend on the structural material composition, shape , etc. At sonic frequencies there is generally less concern with structural damage due to vibration than at low frequencies, where bending modes and much larger displacements can cause failure. Based on criteria used in nuclear power plant piping systems, the allowable limits for the pipe that was used in these experiments was calculated /4./ The results shown in Figure 9, indicate that the vibration limits for the test pipe were not exceeded.

As expected the response of the shaker/pipe system was amplified over a number of frequency ranges due to a multitude of natural modes of vibration. The variance for each 10 s sweep, however, was relatively constant over the duration (typically 24 h) of each experiment and for the three configurations used for the test pipe.
There was evidence of cavitation manifested by the formation of small bubbles in the water at the pipe surface during some of the most positive experiments. It is possible that this contributed to the control of the mussels in these experiments.

6.0 CONCLUSIONS

The experiments conducted in this investigation demonstrated that effective prevention of zebra mussel attachment is possible in structures by the use of solid-borne acoustic energy. The intensity and frequency of acoustic excitation needed was equivalent to about 100 g' on the surface of the structure, between 8 and 14 kHz. Although the vibration amplitude needed for effectiveness appeared to increase with frequency, these were well within the permissible limits for normally operating structures such as piping.

Significant mortality rates were encountered in the higher level exposures. This may be attributed to the sonically induced cavitation as evidenced by the formation of small bubbles near the surface of the structure.

Based on these findings, it is proposed to explore further the use of acoustic energy, both solid and water-borne, for controlling zebra mussel attachment.

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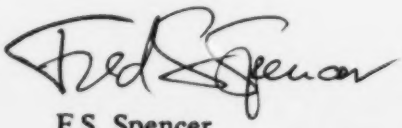

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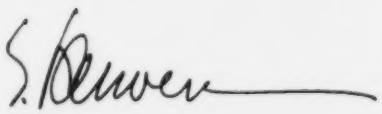

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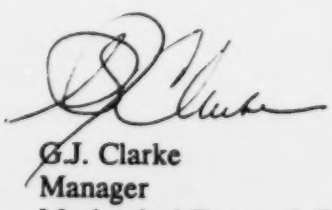

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REFERENCES

1. Kawabe A. Control of macrofouling in Japan: Existing and experimental methods. Symposium on Condenser Macrofouling Control Technologies. EPRI cs.3343 . 1983.

2. Jenner NA. Control of mussel fouling in the Netherlands: Experimental and existing methods. Symposium on Condenser Macrofouling Control Technologies. EPRI cs.3343 . 1983

3. Memorandum from Kowalewski JJ and Patrick PH to Christie AE. Acoustical Control of Zebra Mussels -Progress Report, File no. 833.33, September 19, 1990.

4. ASME/ANSI OM-1987 Standard; Operation and Maintenance of Nuclear Power Plants, The American Society of Mechanical Engineers.

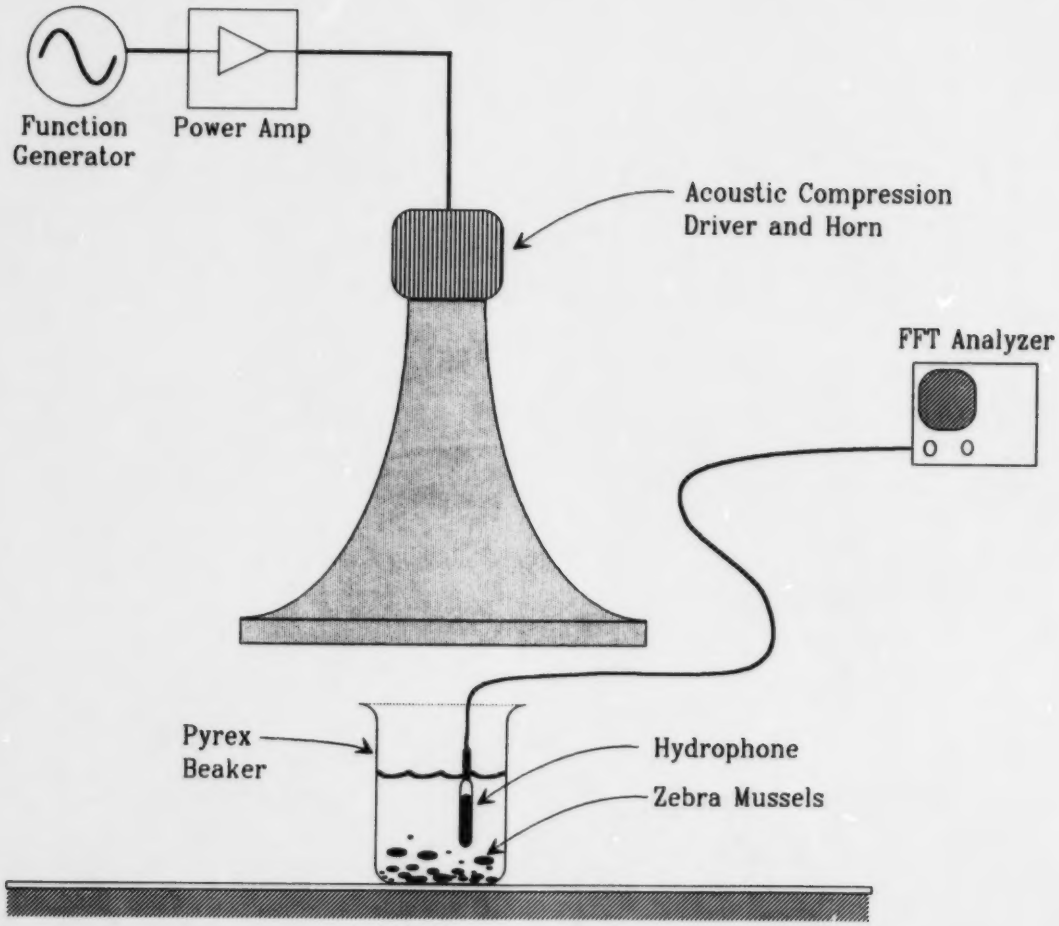


Figure 1 Scoping Test Arrangement with Air to Water-borne Sound

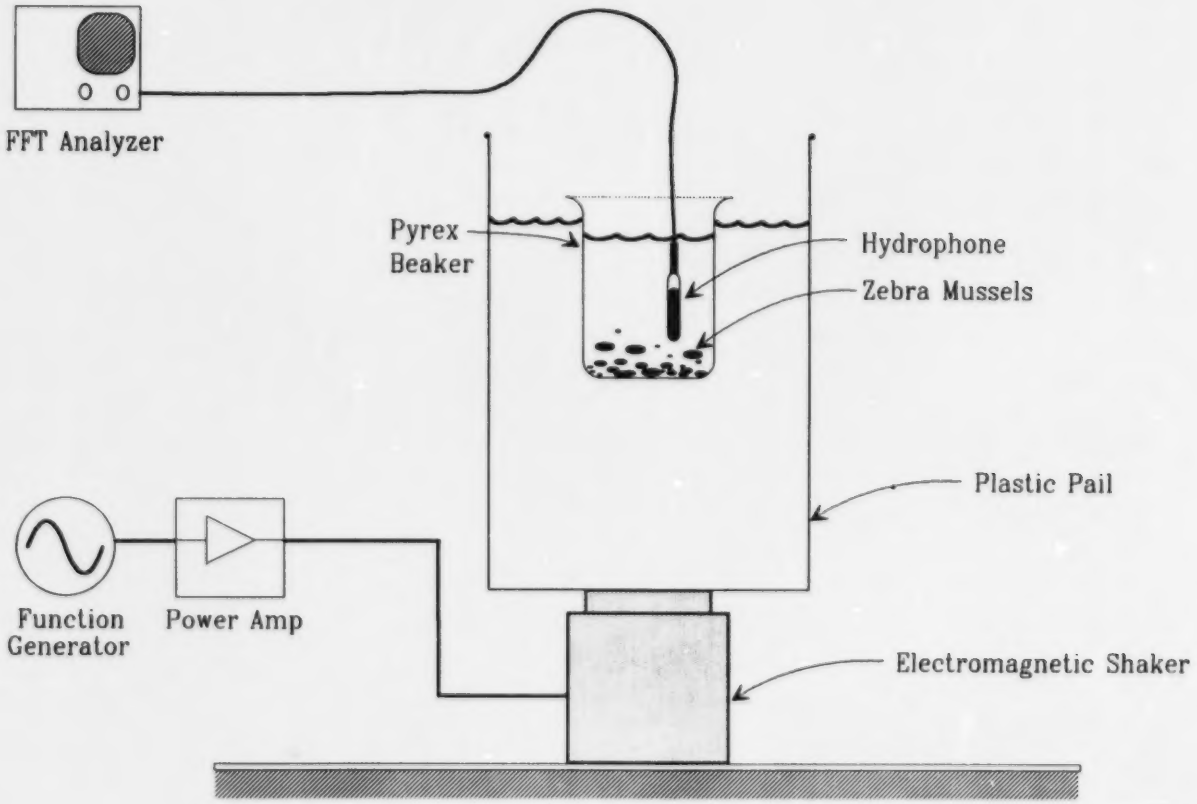


Figure 2 Scoping Test Arrangement with Low Frequency Water-borne Sound

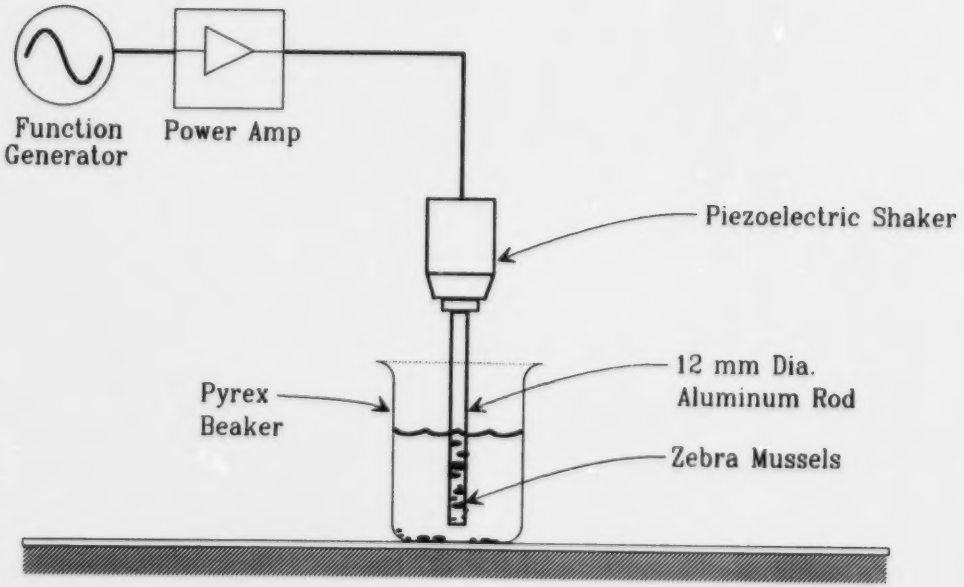
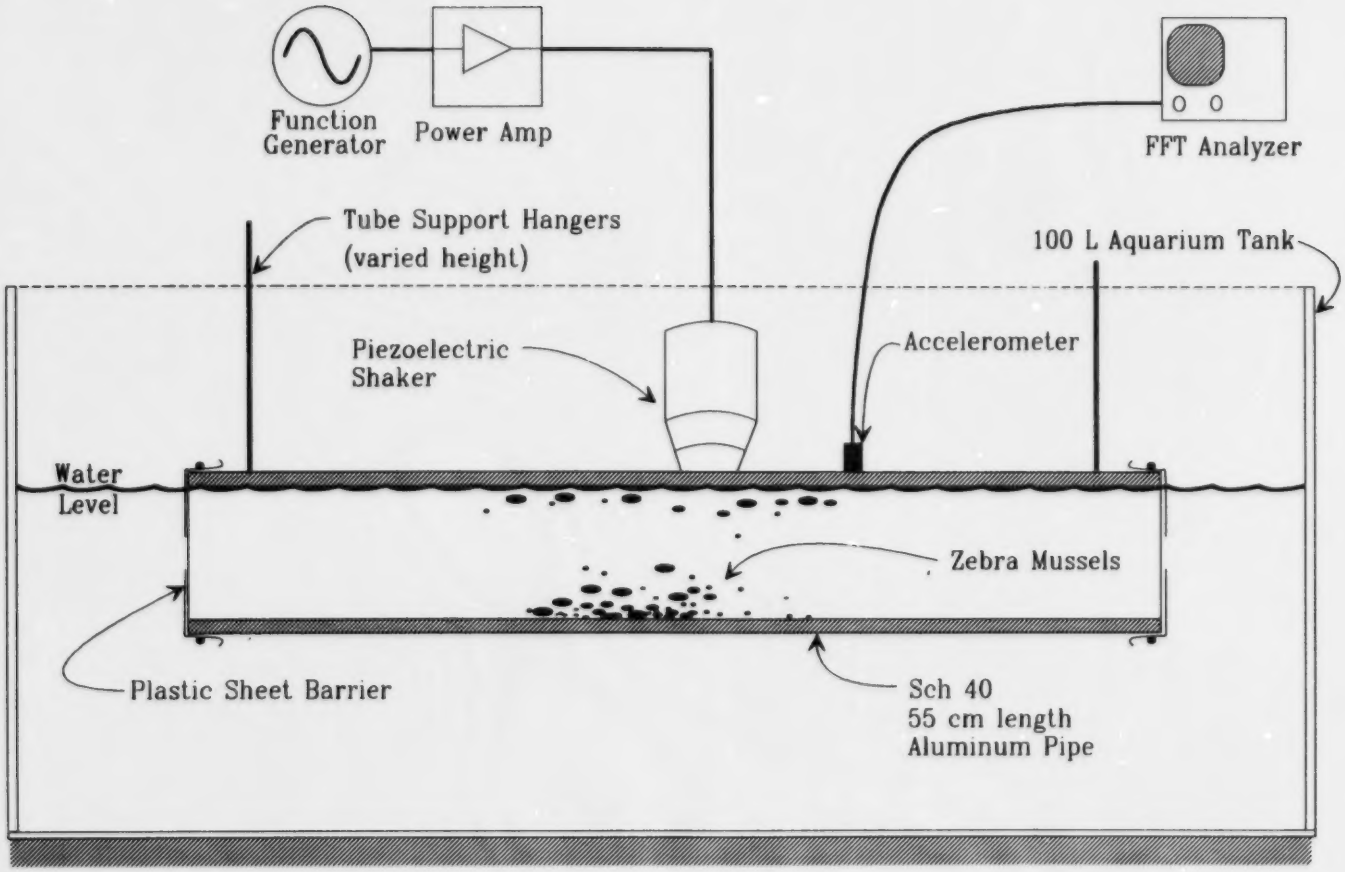


Figure 3 Scoping Test Arrangement with Solid-borne Sound



Side Elevation View

Figure 4 Test Arrangement for Zebra Mussles Prevention Experiments.

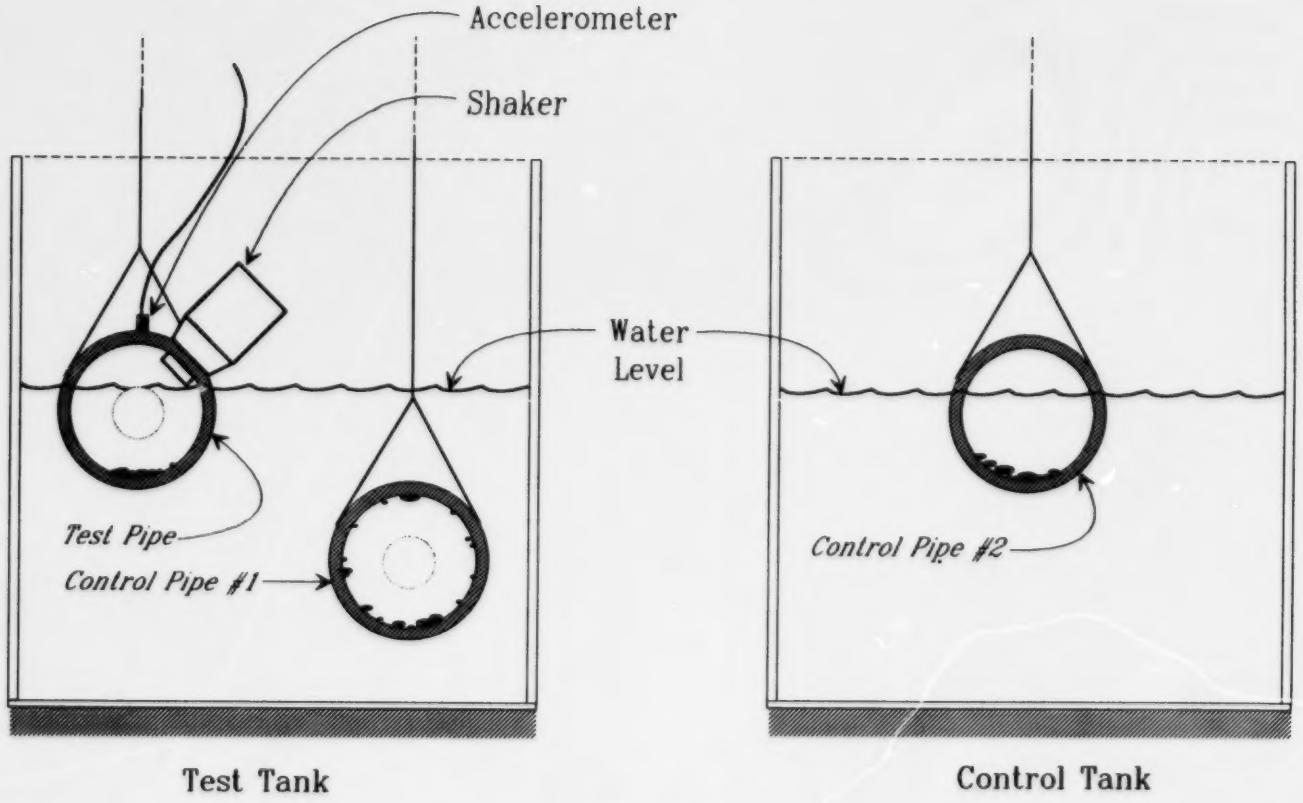


Figure 5 Test Arrangement 'A'

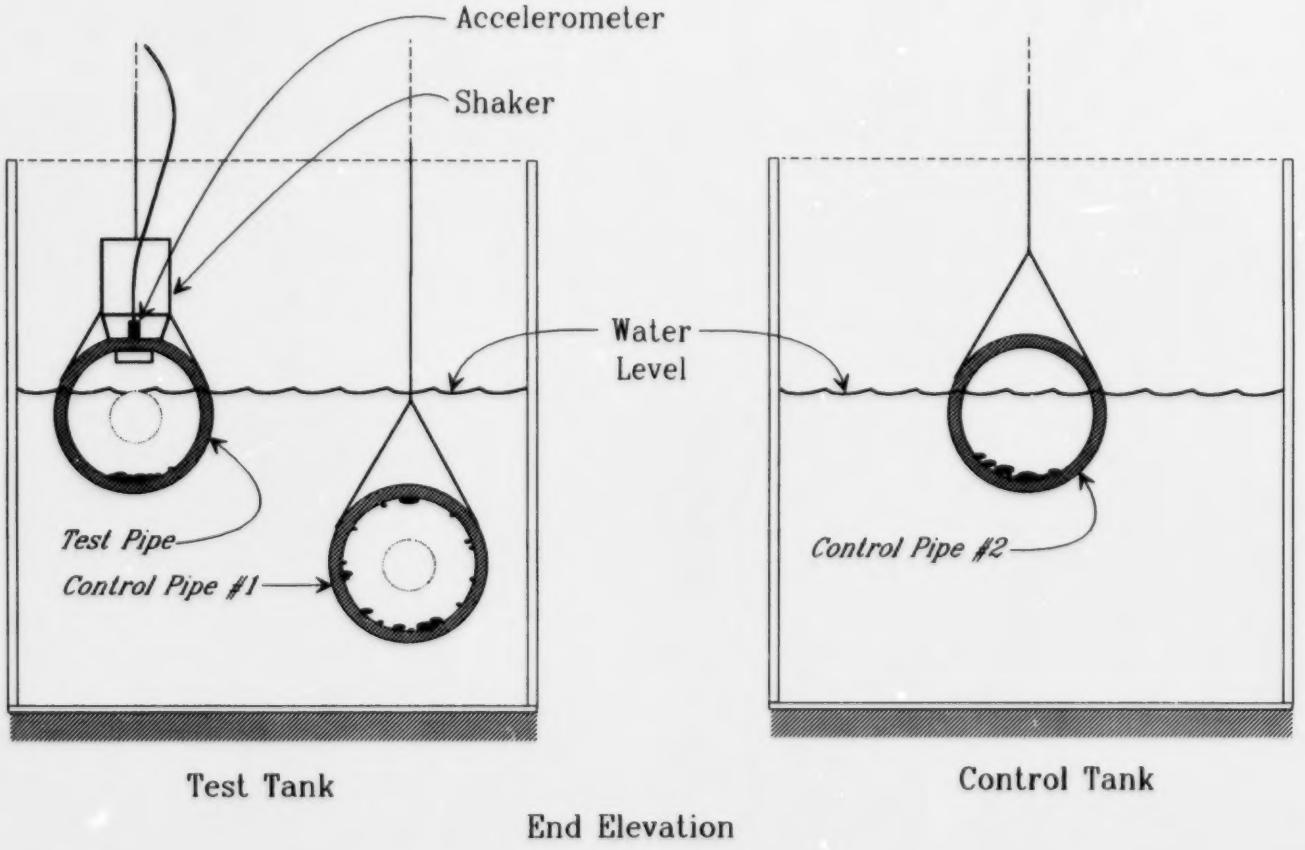


Figure 6 Test Arrangement 'B'

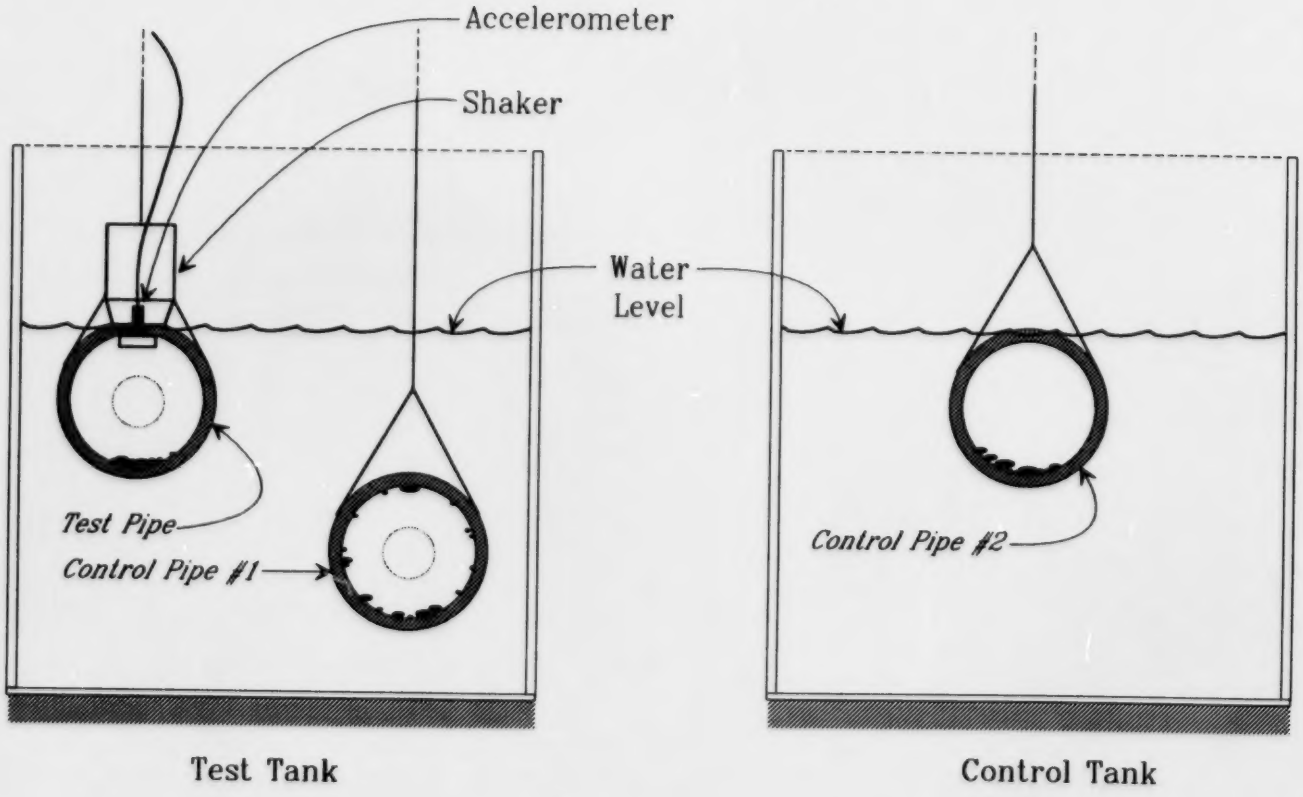


Figure 7 Test Arrangement 'C'

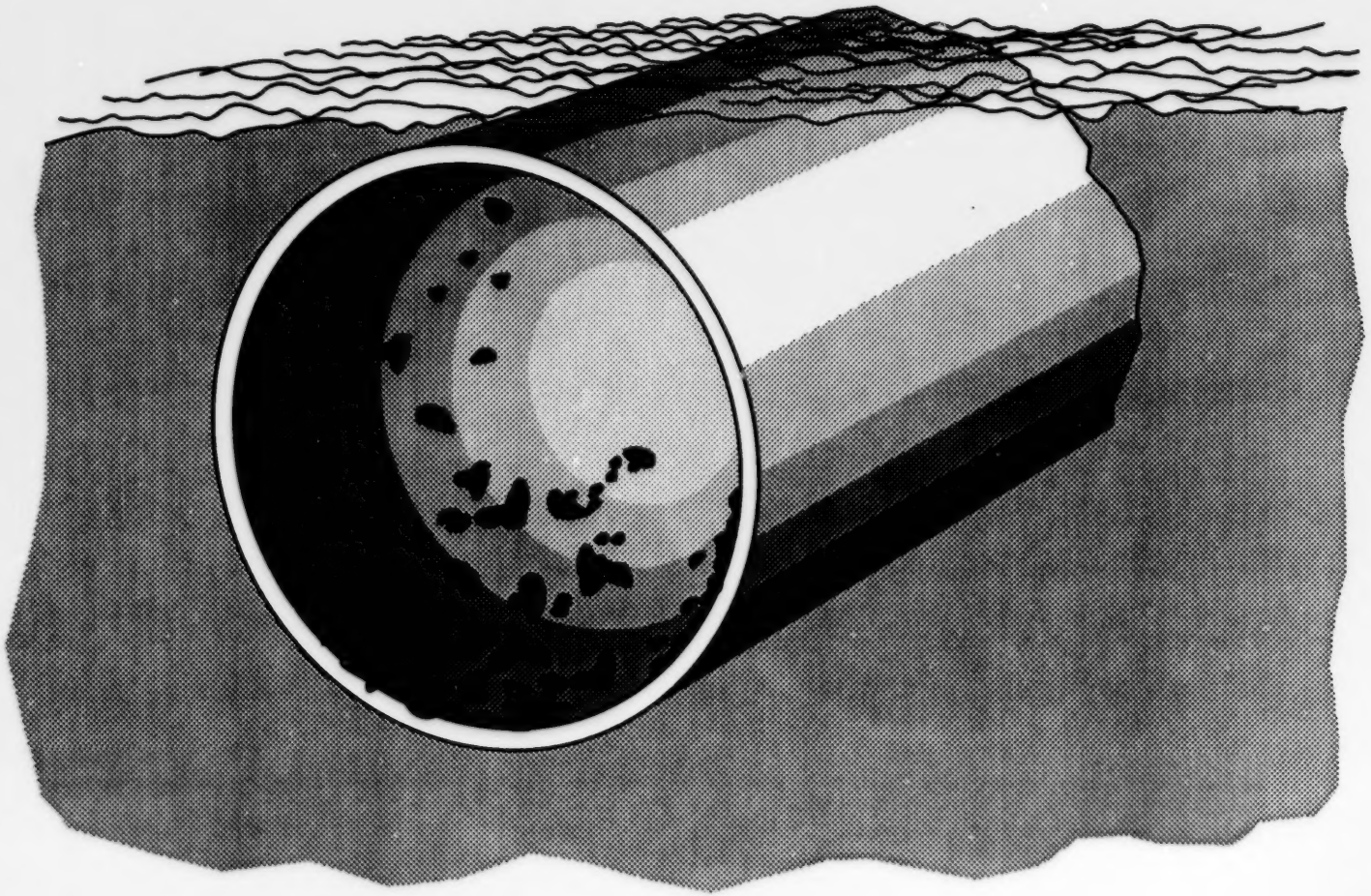


FIGURE 8

TYPICAL DISTRIBUTION OF ZEBRA MUSSELS IN THE CONTROL PIPE

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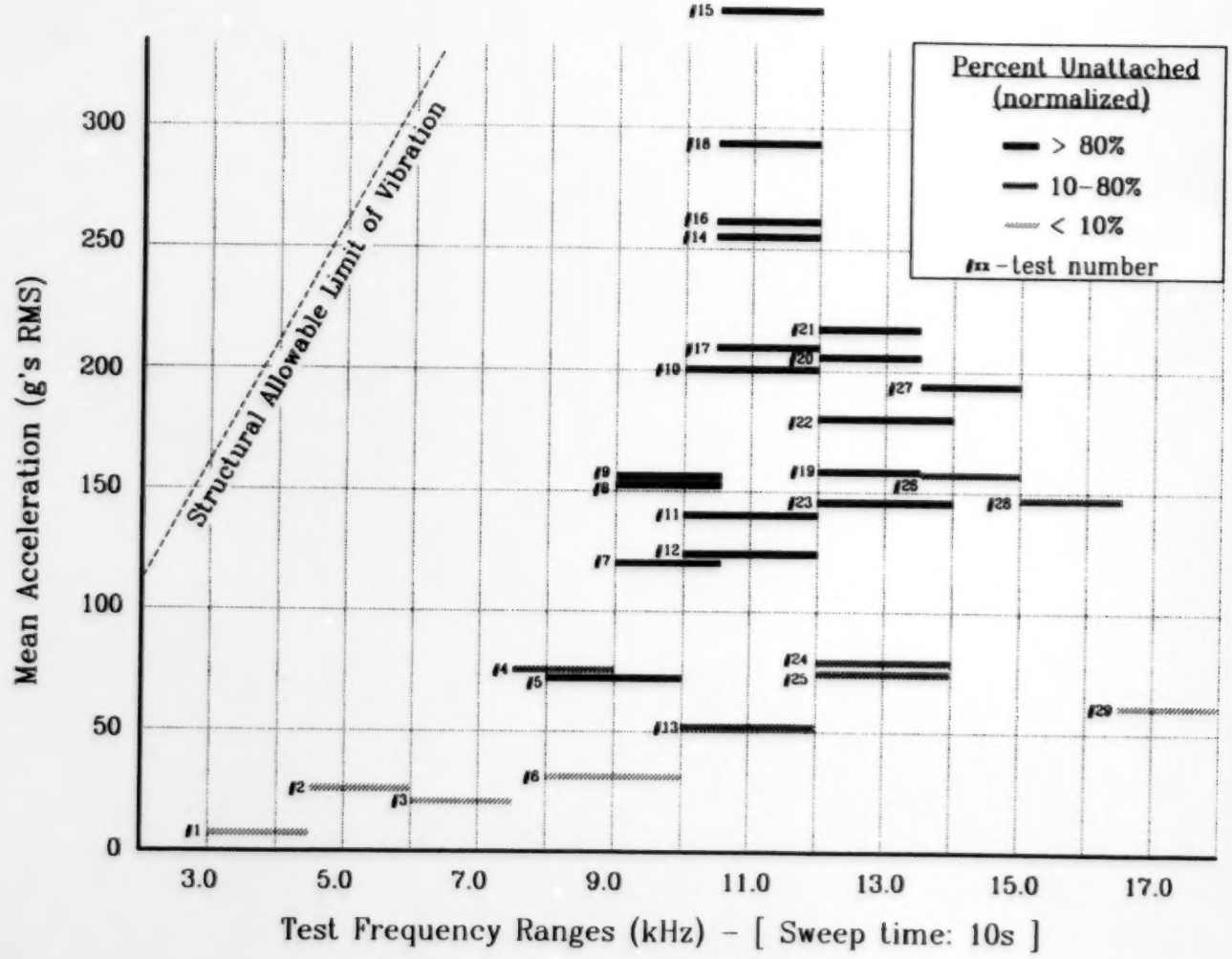


Figure 9 – Summary of Acoustical Experiments for Controlling Zebra Mussel Attachment

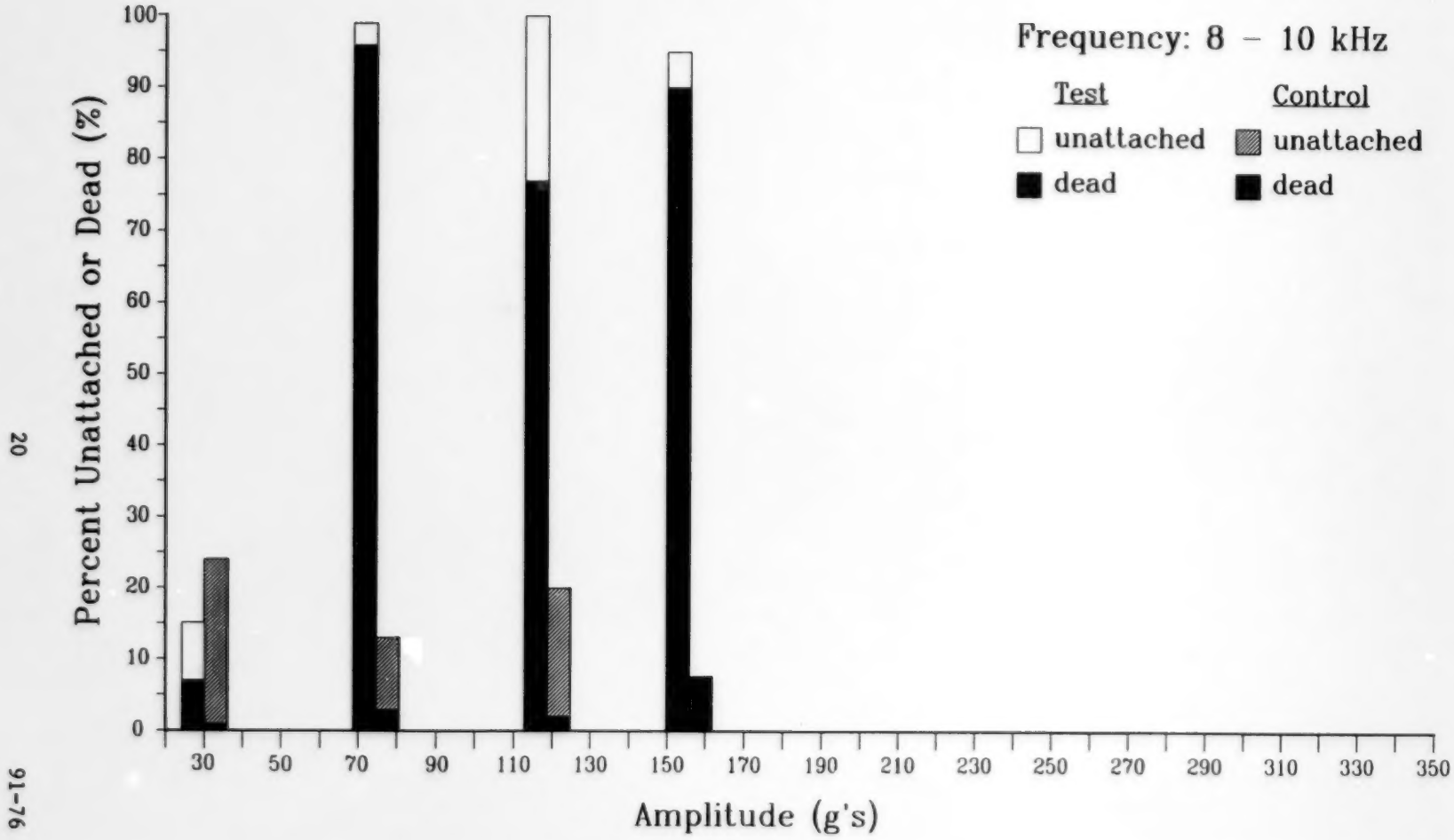


Figure 10 – Effect of Amplitude on Zebra Mussel Attachment

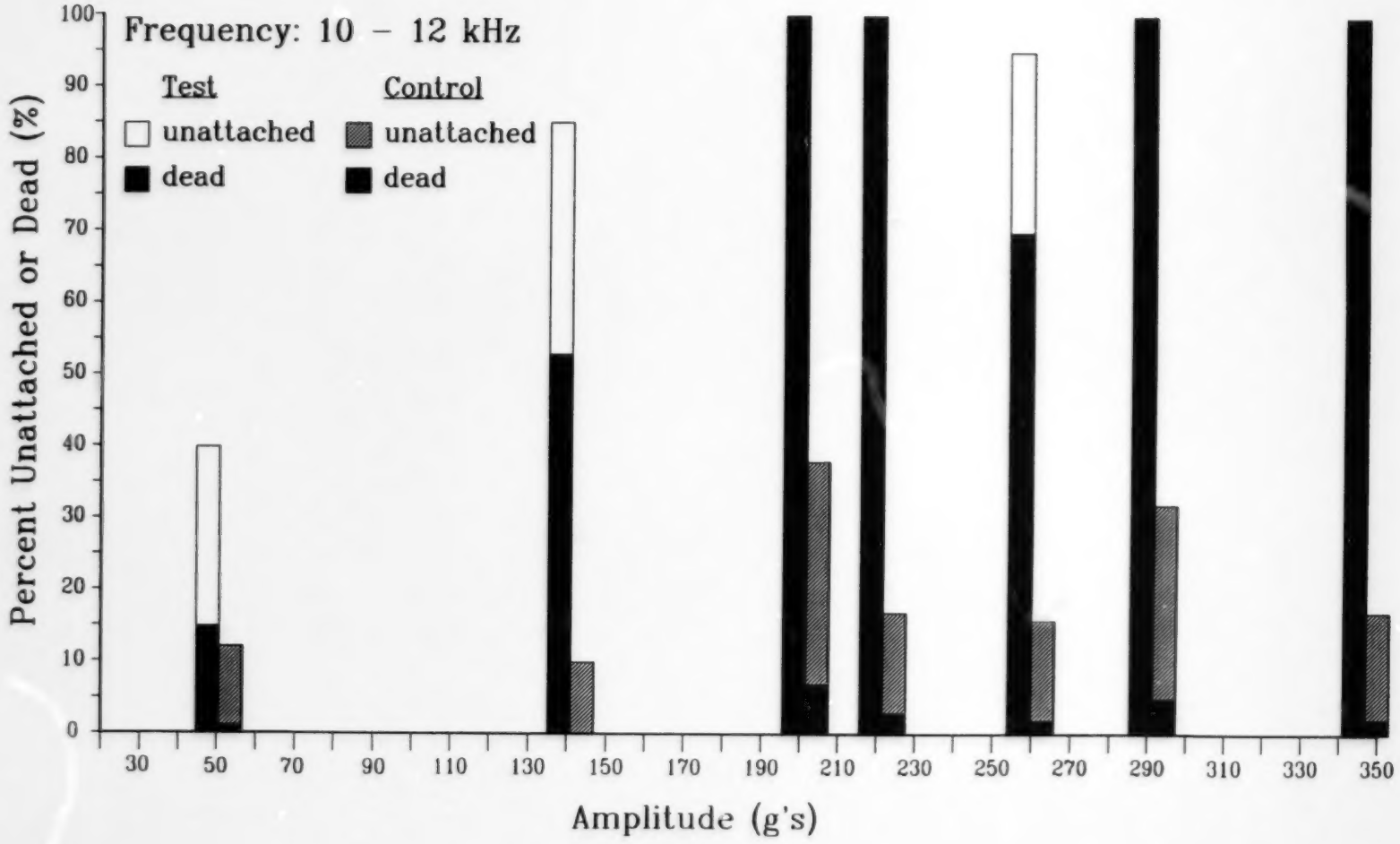


Figure 11 – Effect of Amplitude on Zebra Mussel Attachment

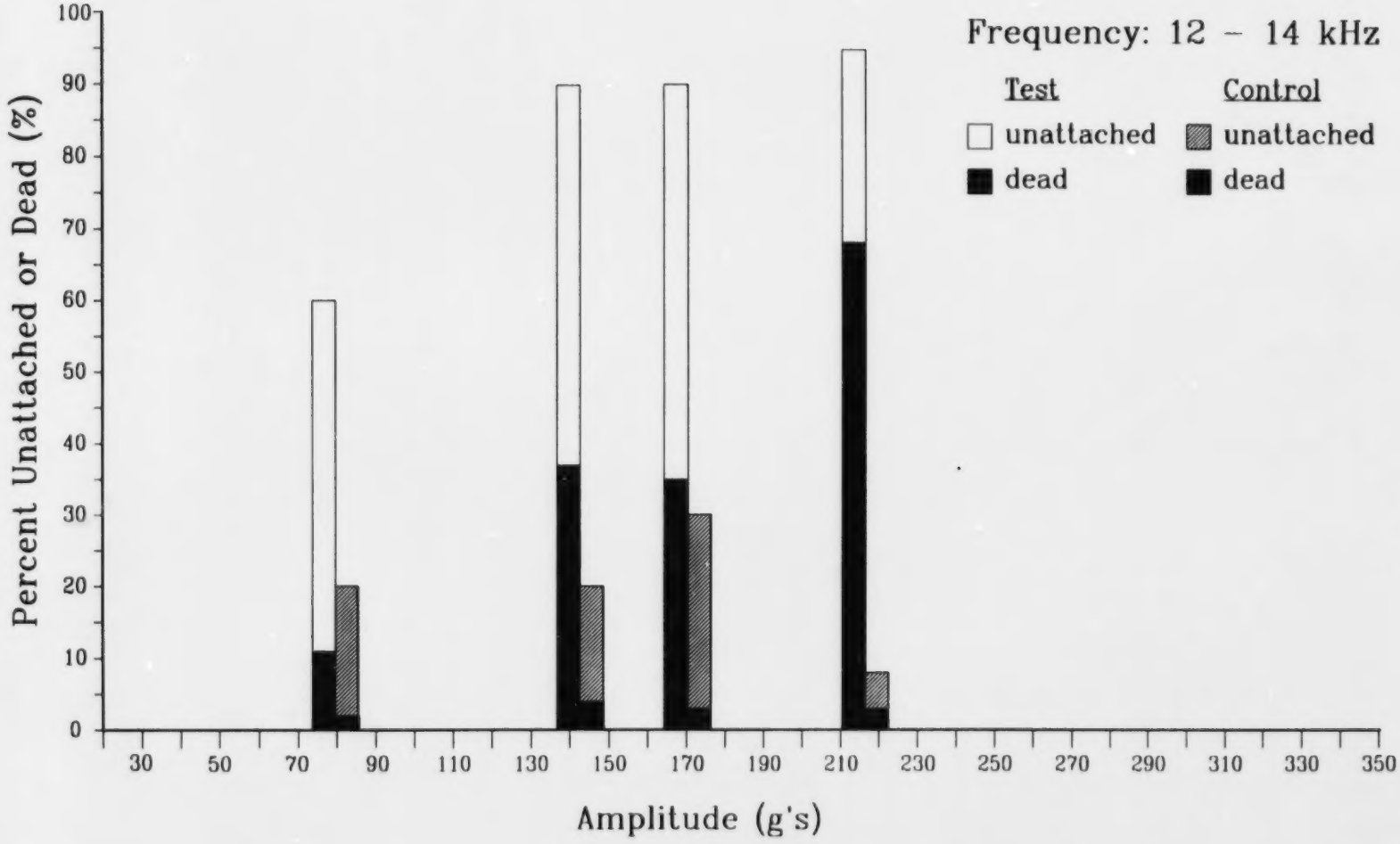


Figure 12 - Effect of Amplitude on Zebra Mussel Attachment

FIGURE 13

CONDITION OF JUVENILE ZEBRA MUSSELS AFTER EXPOSURE TO ACOUSTIC ENERGY

APPENDIX A

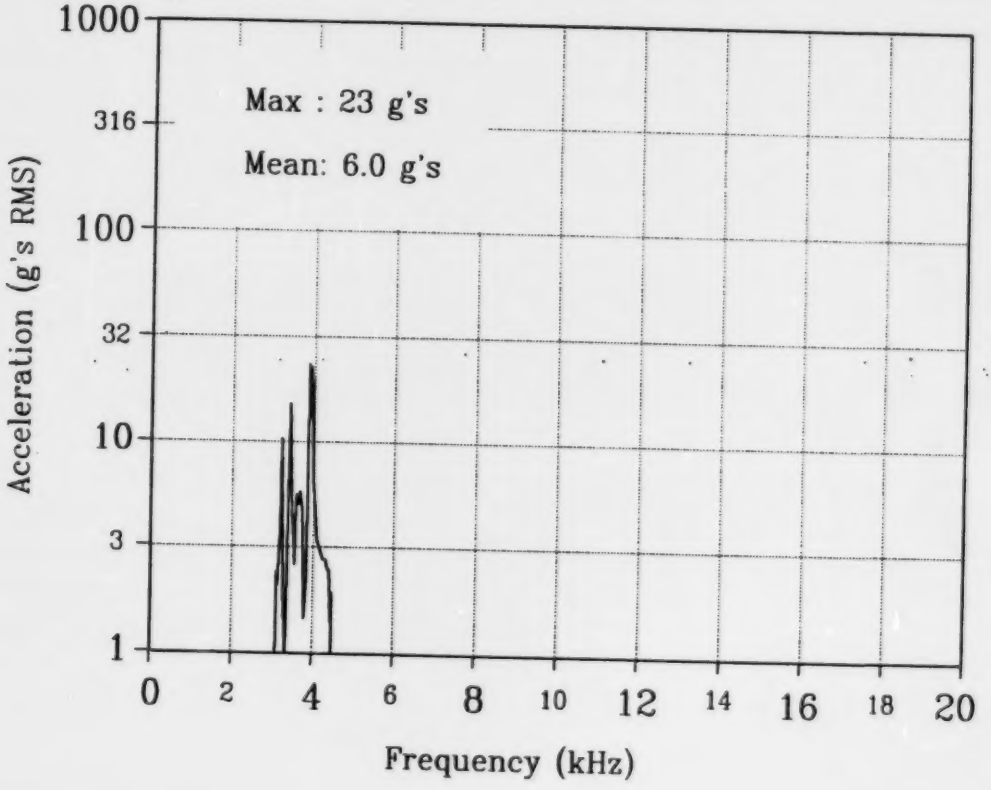
Laboratory Acoustical Experiments Data and Results - Figures A-1 to A29

Test Arrangement: A (see Figure 5)

Frequency Range: 3.0 – 4.5 kHz. Duration: 64 hrs.

Drive Input: 1.0 V Date: August 24/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 12%
Control 12%

Figure A–1

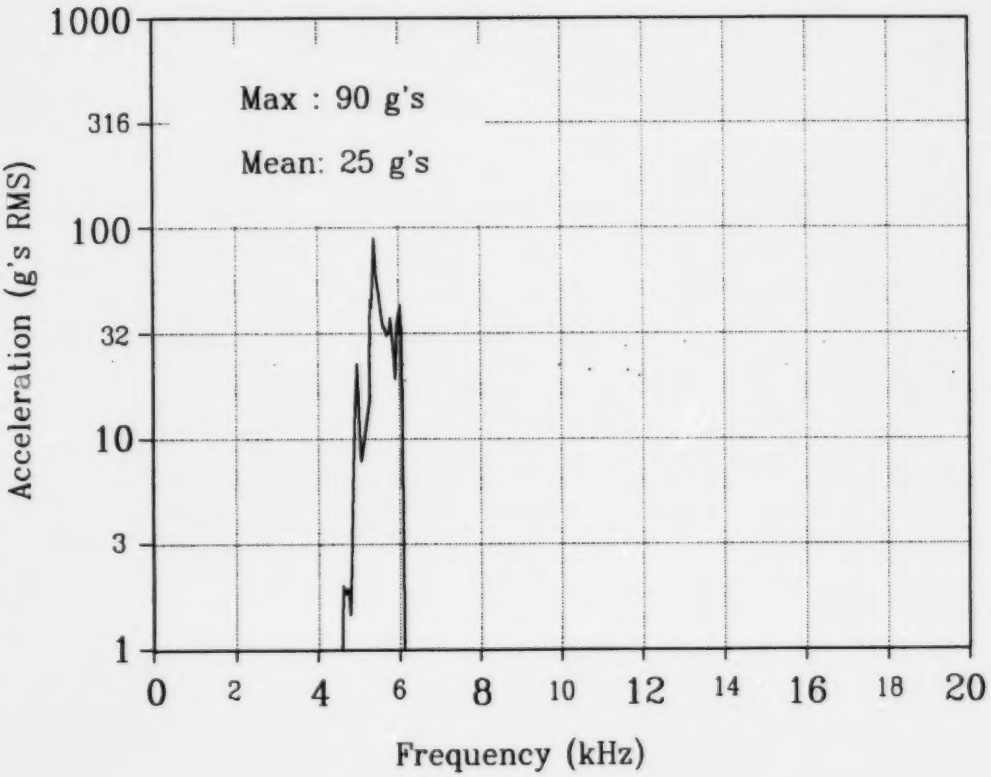
Test No 01 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 4.5 – 6.0 kHz. Duration: 23 hrs.

Drive Input: 1.0 V Date: August 27/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 8%
Control 8%

Figure A–2

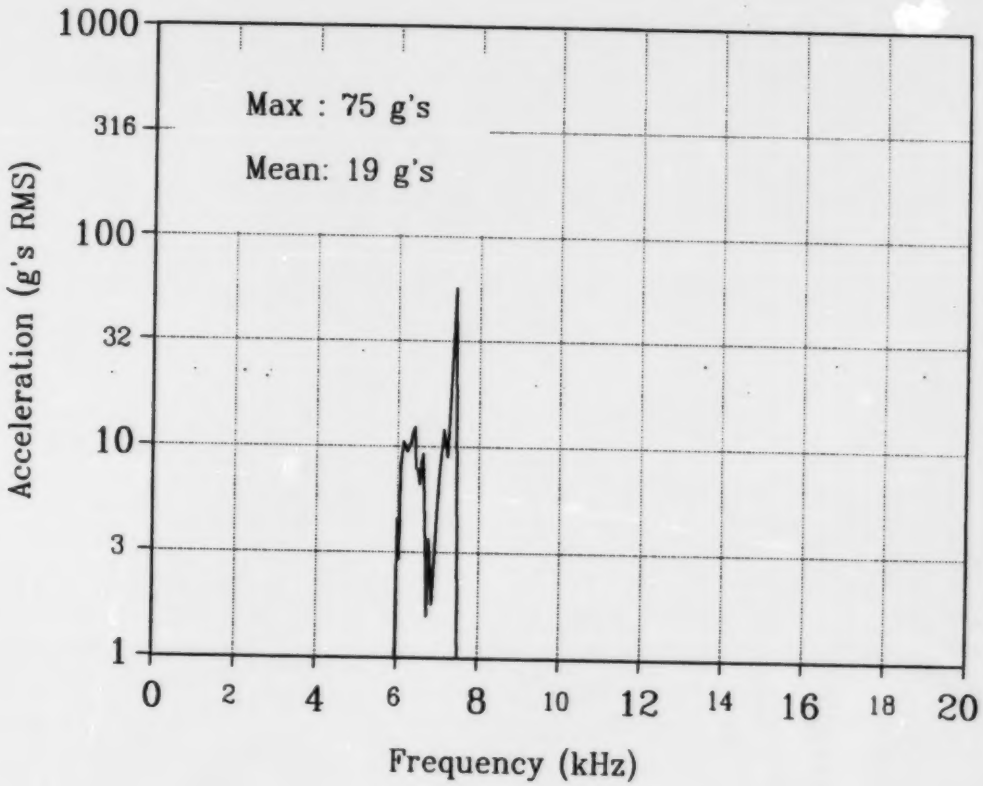
Test No 02 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 6.0 – 7.5 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: August 28/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test <10%
Control <10%

Figure A–3

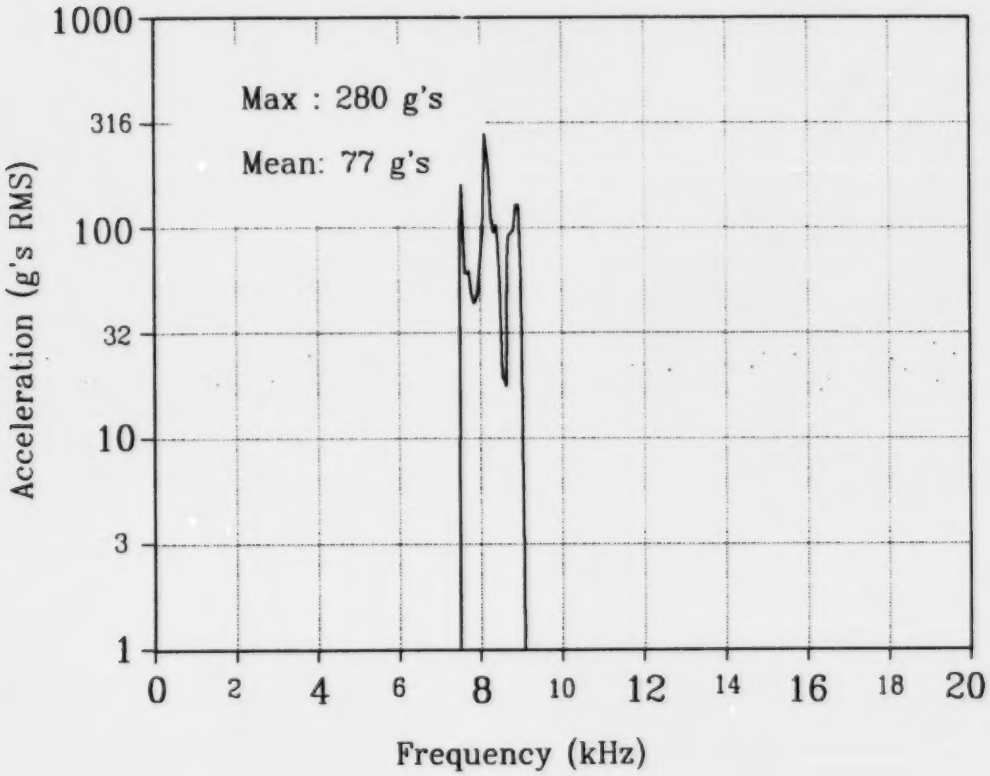
Test No 03 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 7.5 – 9.0 kHz. Duration: 21 hrs.

Drive Input: 1.0 V Date: August 29/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 50%
Control 18%

Figure A–4

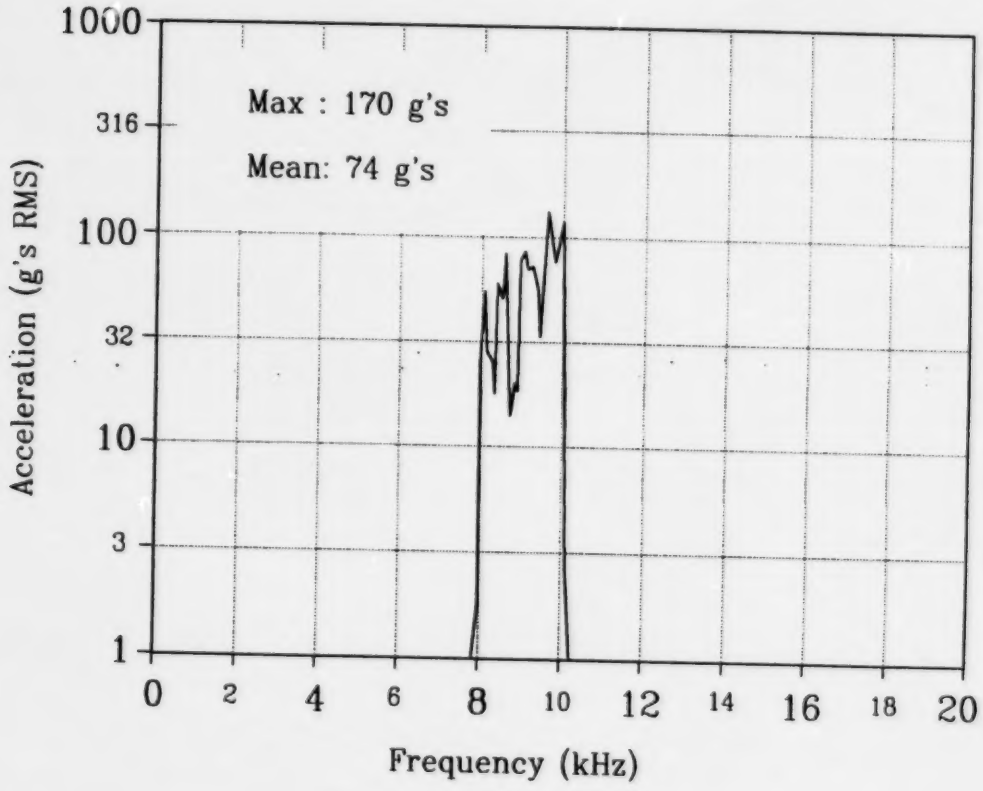
Test No 04 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 8.0 – 10.0 kHz. Duration: 16 hrs.

Drive Input: 1.0 V Date: October 29/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 99%
Control 13%

Figure A–5

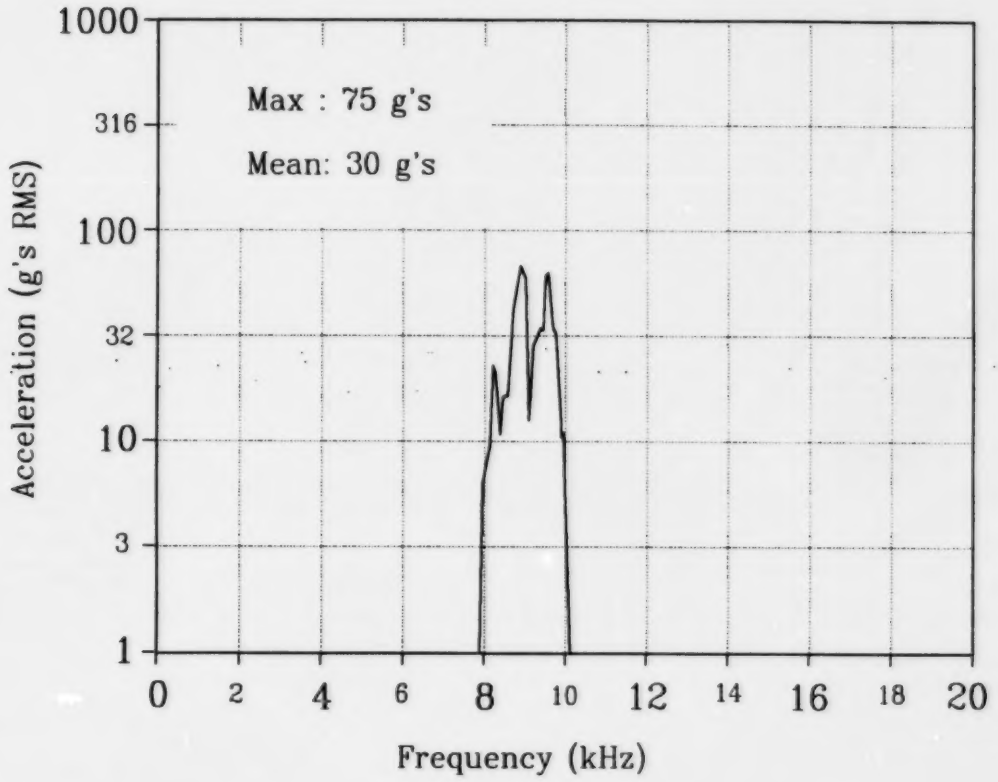
Test No 05 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 8.0 – 10.0 kHz. Duration: 47 hrs.

Drive Input: 0.5 V Date: October 31/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 15%
Control 24%

Figure A–6

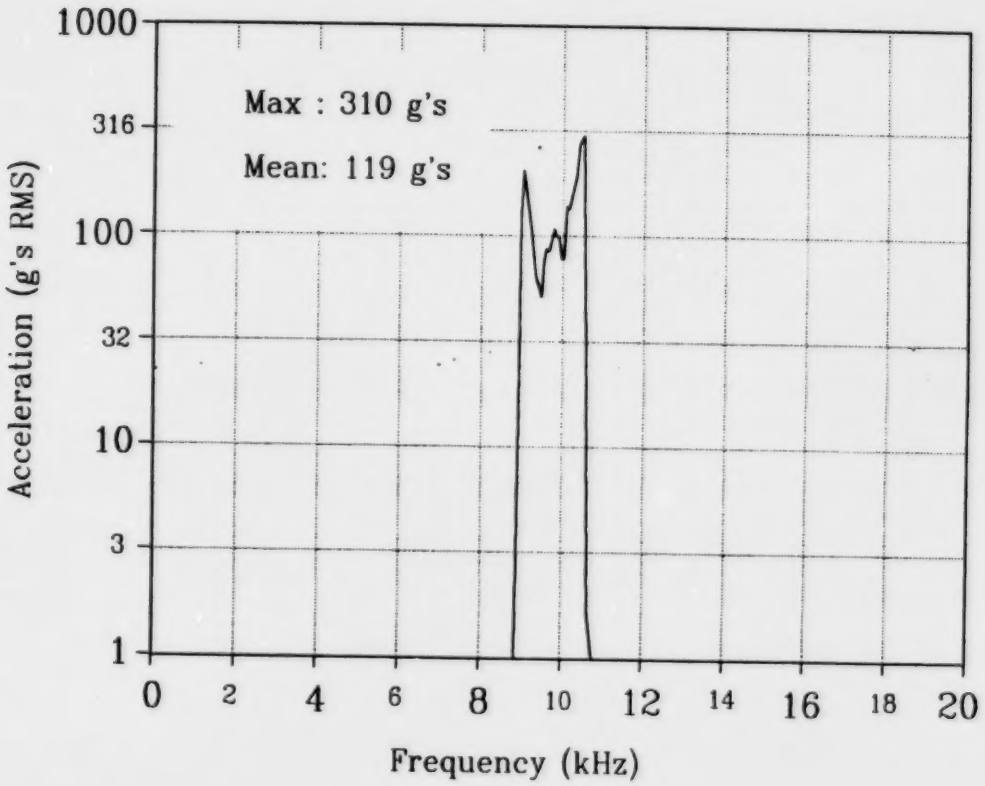
Test No 06 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 9.0 – 10.5 kHz. Duration: 22 hrs.

Drive Input: 1.0 V Date: August 30/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 20%

Figure A–7

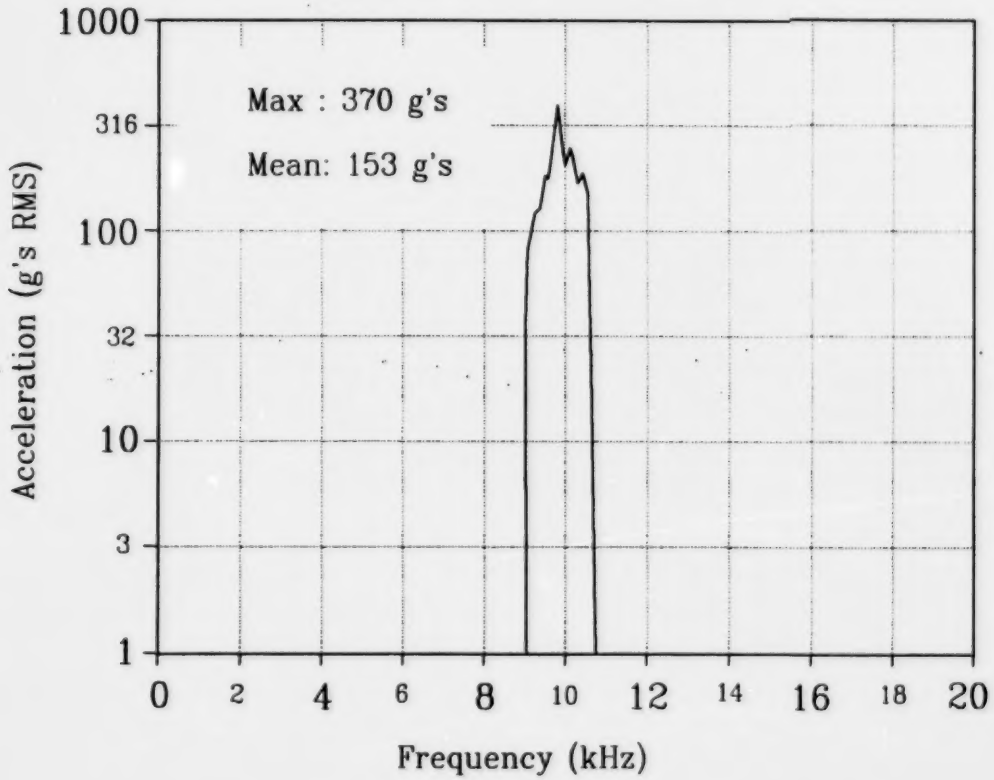
Test No 07 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 9.0 – 10.5 kHz. Duration: 19 hrs.

Drive Input: 1.0 V Date: September 18/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 13%

Figure A-8

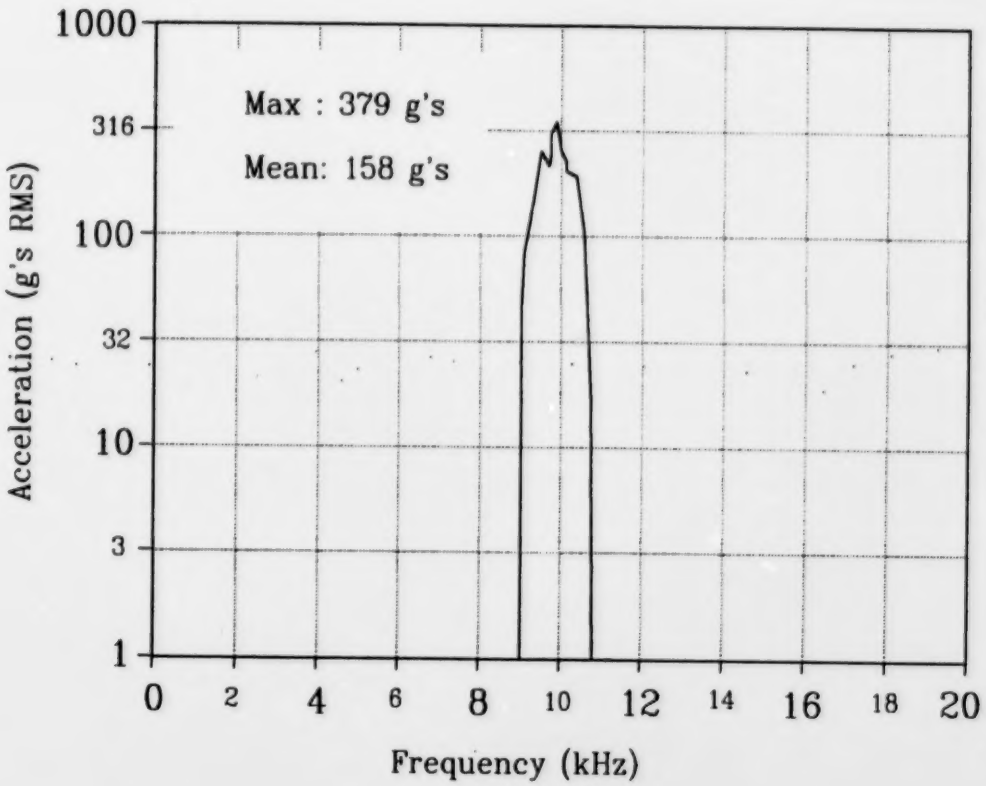
Test No 08 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: B (see Figure 6)

Frequency Range: 9.0 – 10.5 kHz. Duration: 27 hrs.

Drive Input: 1.0 V Date: September 19/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 90%
Control 2%

Figure A–9

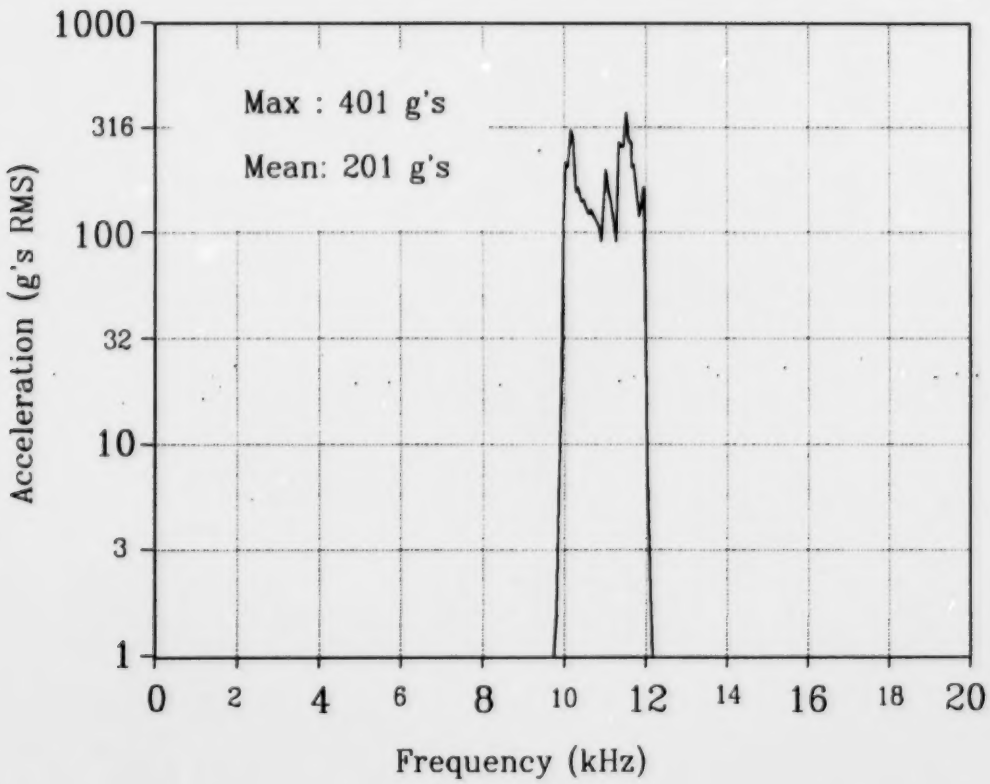
Test No 09 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 10.0 – 12.0 kHz. Duration: 19 hrs.

Drive Input: 1.0 V Date: November 7/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 38%

Figure A–10

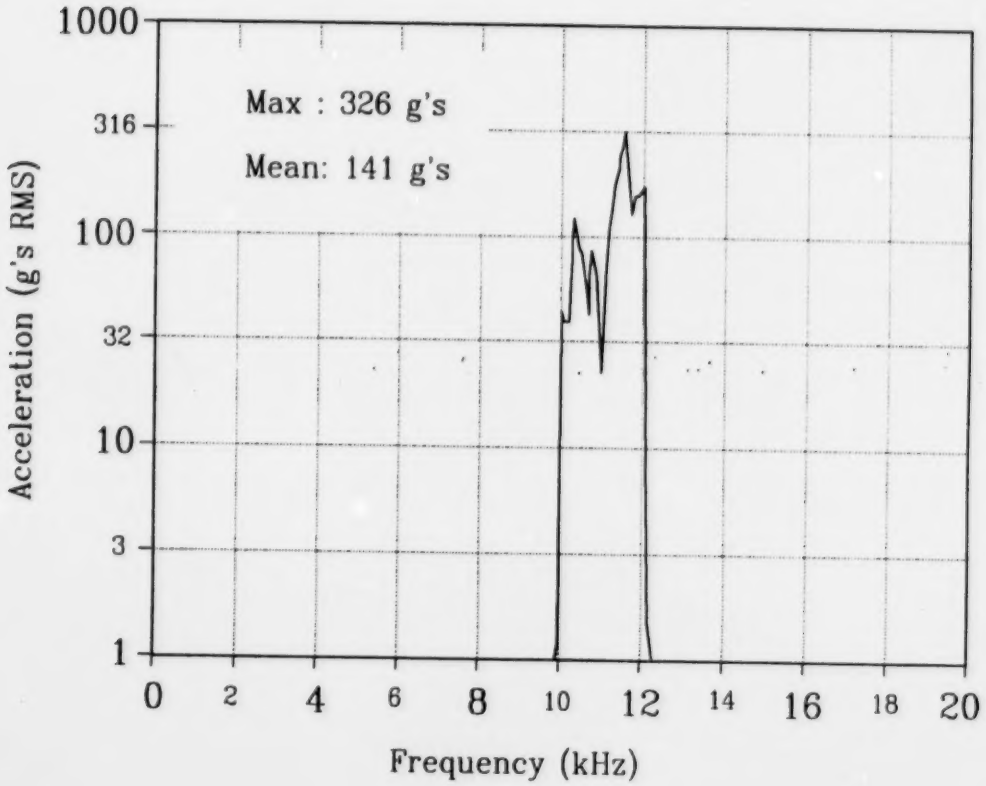
Test No 10 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 10.0 – 12.0 kHz. Duration: 4 hrs.

Drive Input: 0.5 V Date: October 19/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 85%
Control 10%

Figure A–11

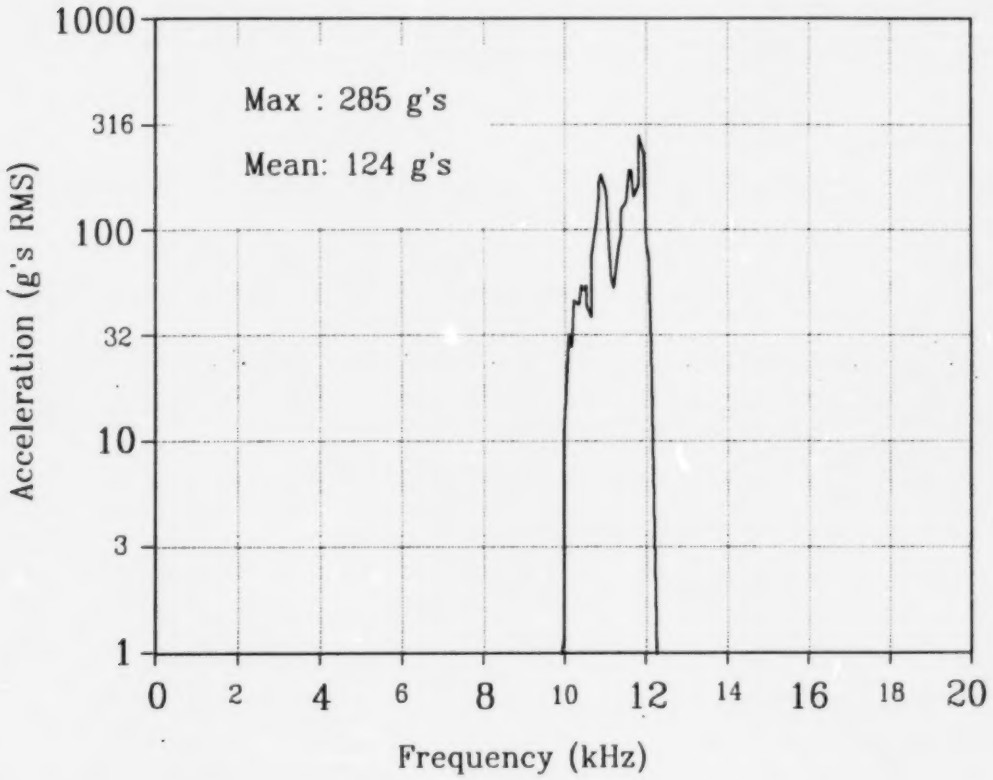
Test No 11 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 10.0 – 12.0 kHz. Duration: 4 hrs.

Drive Input: 0.5 V Date: October 26/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 – 3.0 mm

Percent unattached: Test ~90%
Control ~10%

Figure A–12

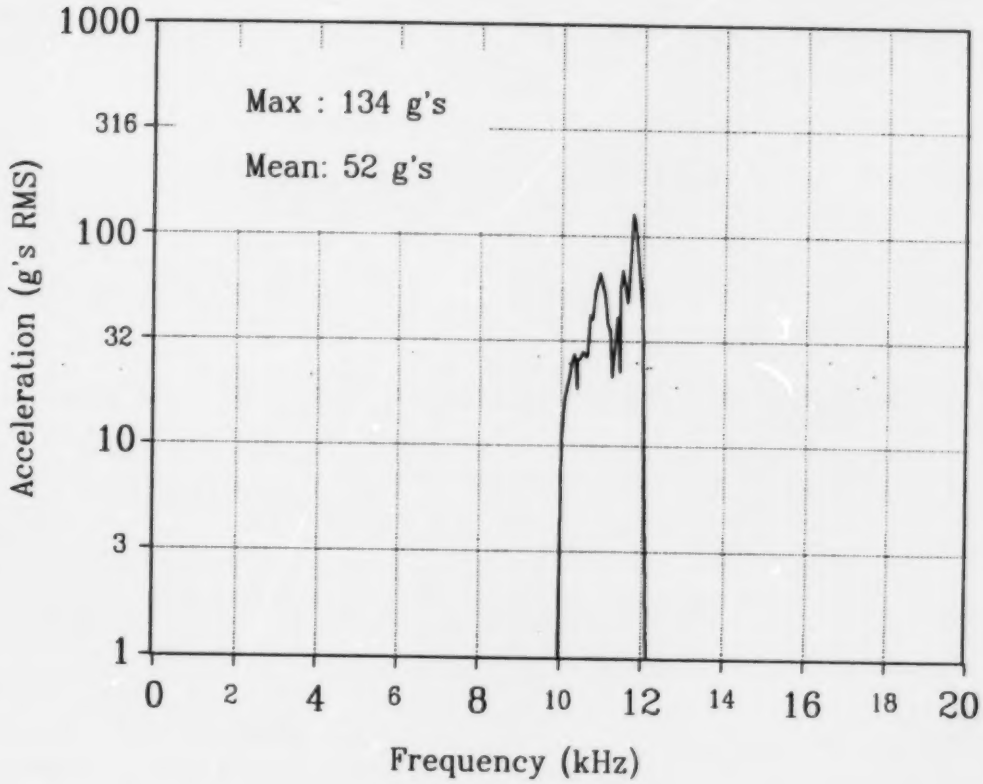
Test No 12 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 10.0 – 12.0 kHz. Duration: 61 hrs.

Drive Input: 0.25 V Date: October 26/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 – 3.0 mm

Percent unattached: Test 40%
Control 12%

Figure A–13

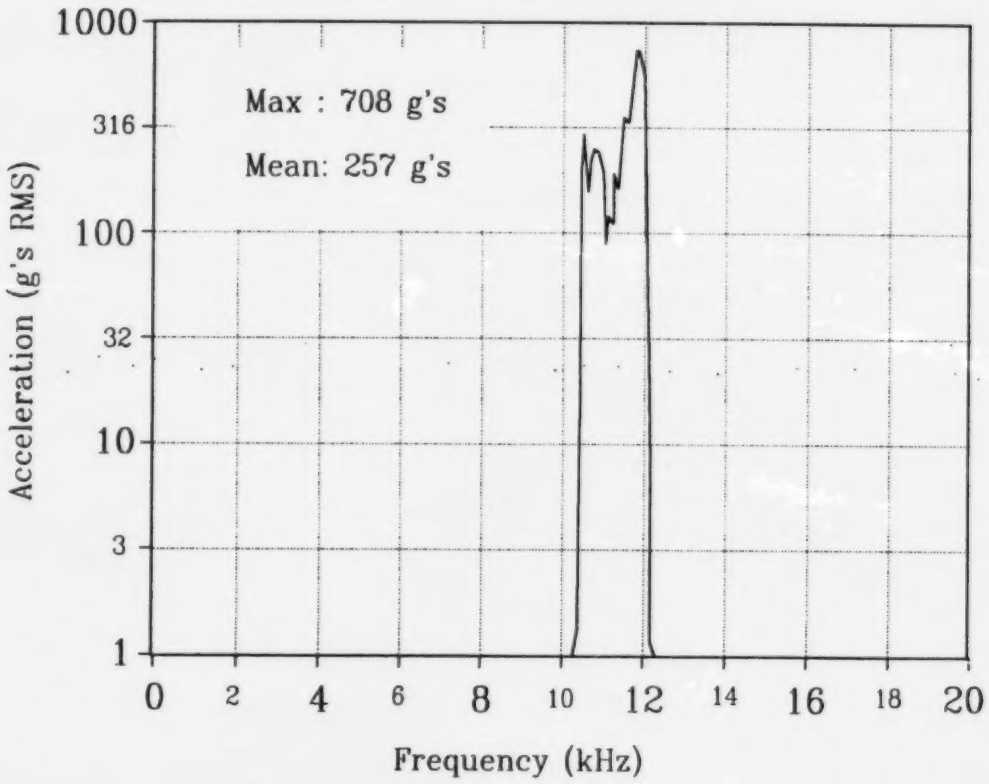
Test No 13 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: B (see Figure 6)

Frequency Range: 10.5 – 12.0 kHz. Duration: 21 hrs.

Drive Input: 1.0 V Date: September 26/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 14%

Figure A–14

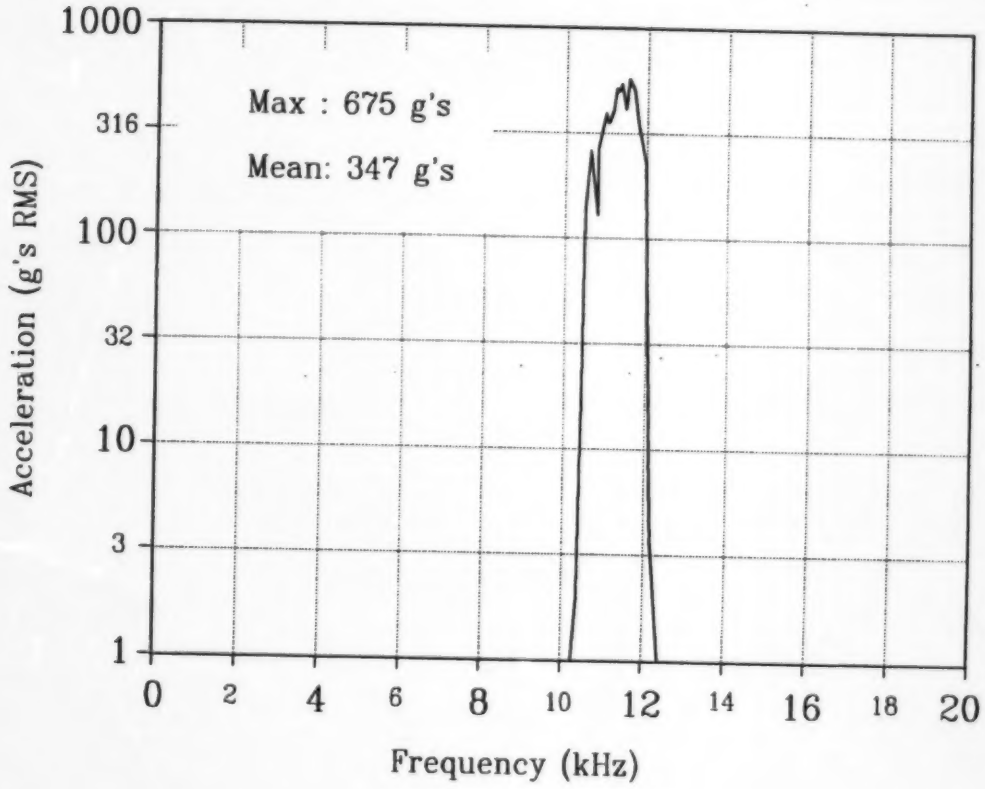
Test No 14 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 10.5 – 12.0 kHz. Duration: 3 hrs.

Drive Input: 1.0 V Date: November 2/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 17%

Figure A–15

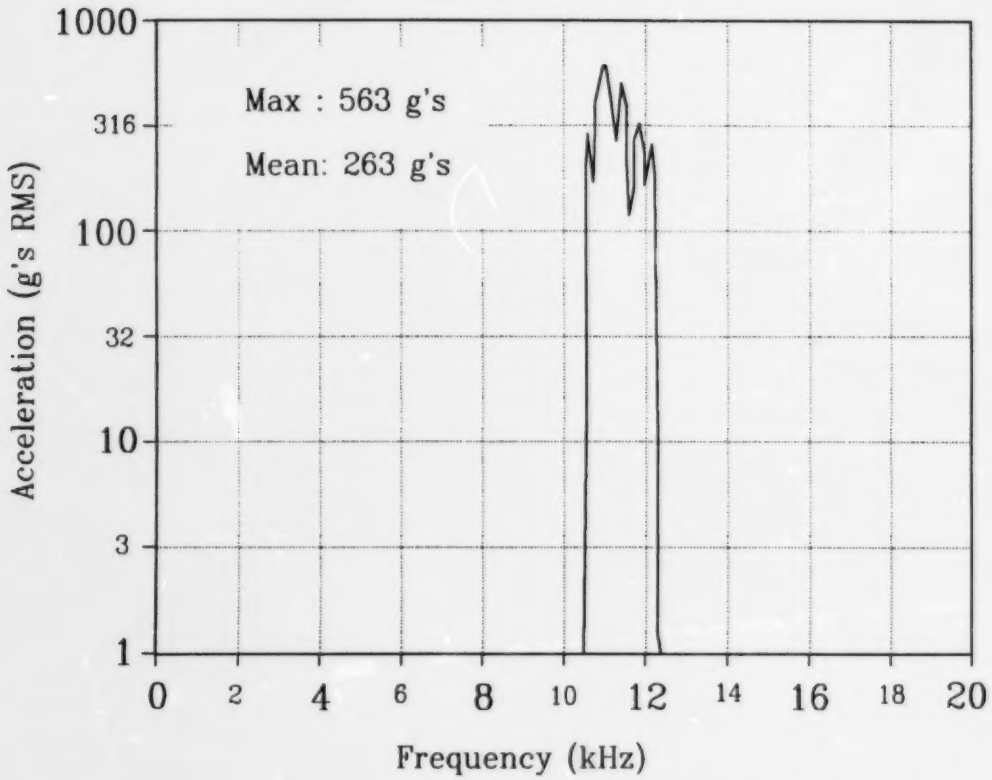
Test No 15 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 10.5 – 12.0 kHz. Duration: 20 hrs.

Drive Input: 1.0 V Date: September 4/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 5.0 mm

Percent unattached: Test 90%
Control 19%

Figure A–16

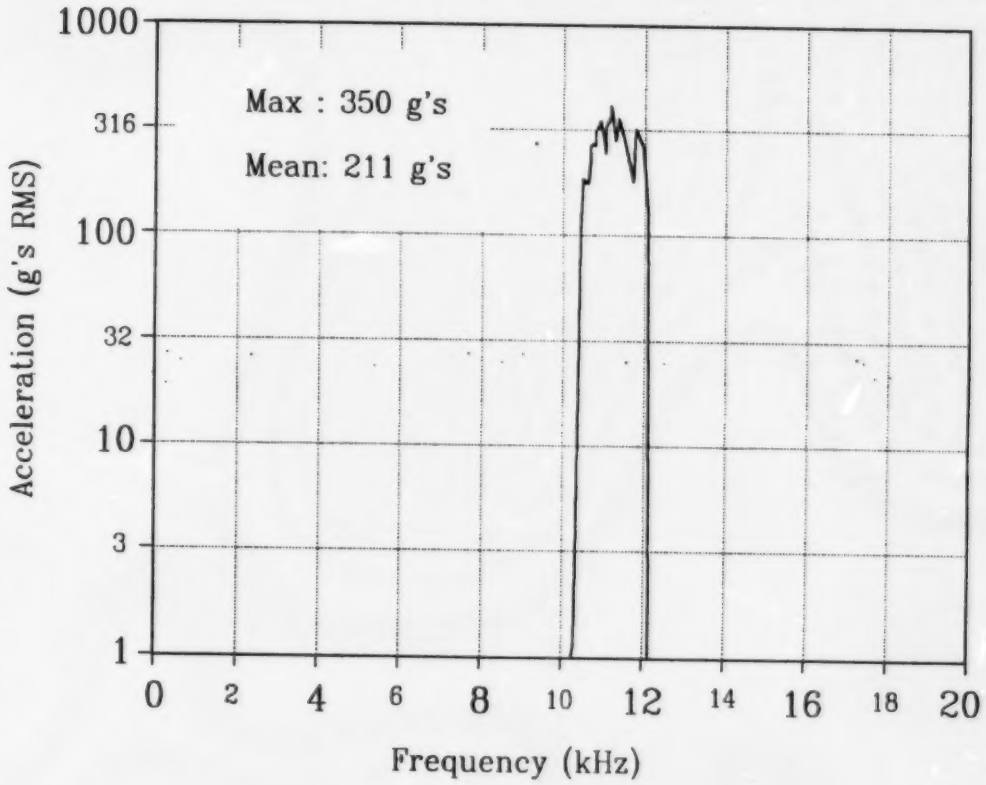
Test No 16 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: B (see Figure 6)

Frequency Range: 10.5 – 12.0 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: September 25/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 17%

Figure A–17

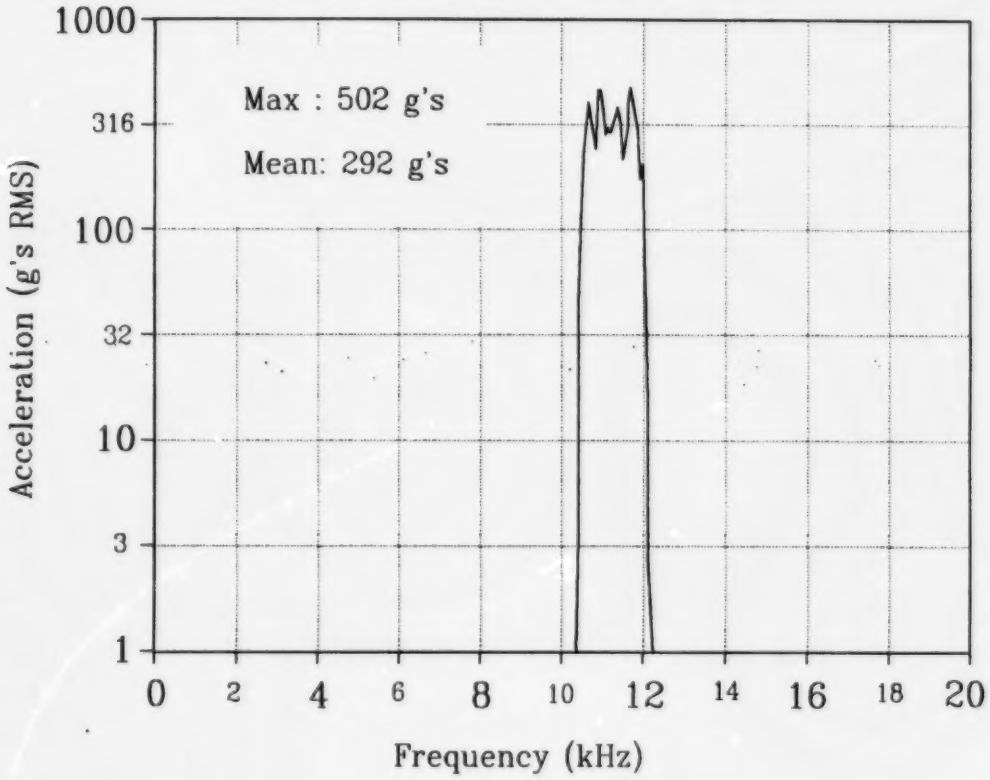
Test No 17 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 10.5 – 12.0 kHz. Duration: 41 hrs.

Drive Input: 1.0 V Date: November 5/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 100%
Control 32%

Figure A–18

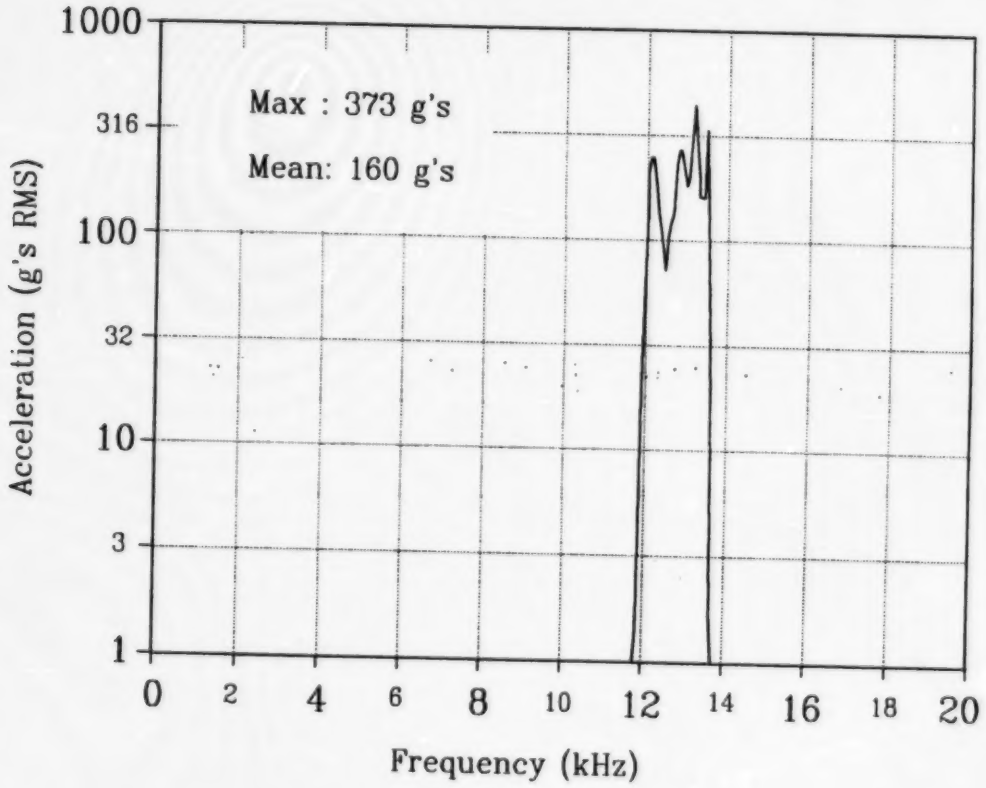
Test No 18 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 12.0 – 13.5 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: September 5/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 90%

Control 33%

Figure A–19

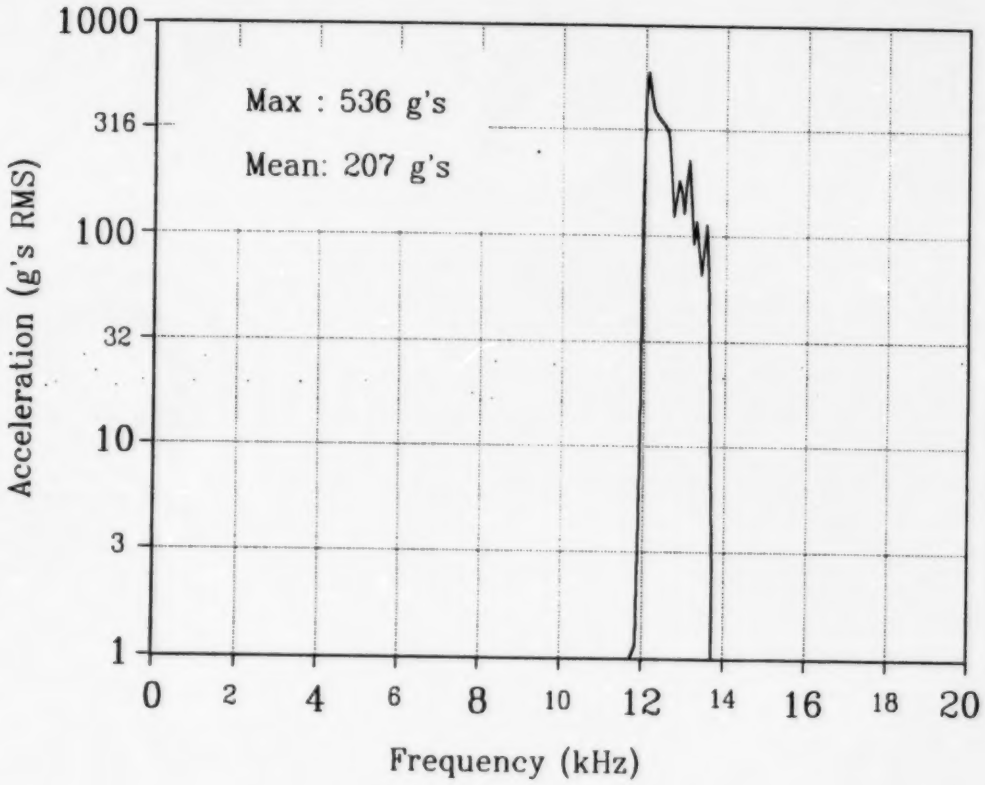
Test No 19 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: B (see Figure 6)

Frequency Range: 12.0 – 13.5 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: September 27/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 – 5.0 mm

Percent unattached: Test 90%

Control 5%

Figure A–20

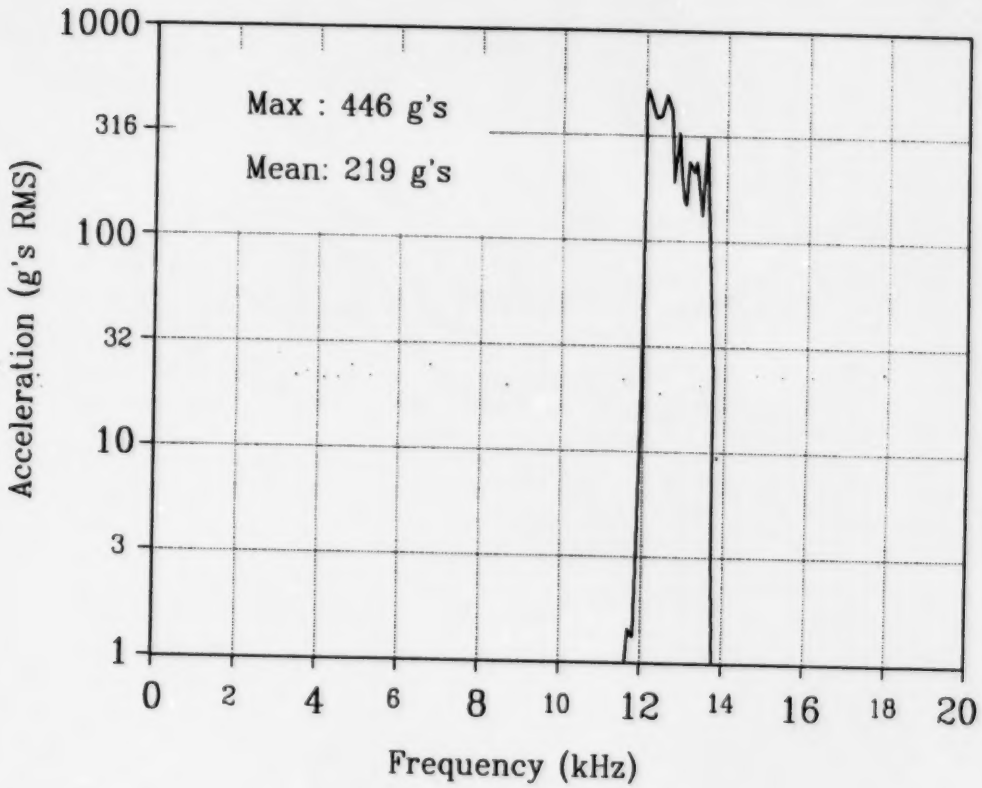
Test No 20 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: B (see Figure 6)

Frequency Range: 12.0 - 13.5 kHz. Duration: 22 hrs.

Drive Input: 1.0 V Date: October 1/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 - 3.0 mm

Percent unattached: Test 100%
Control 12%

Figure A-21

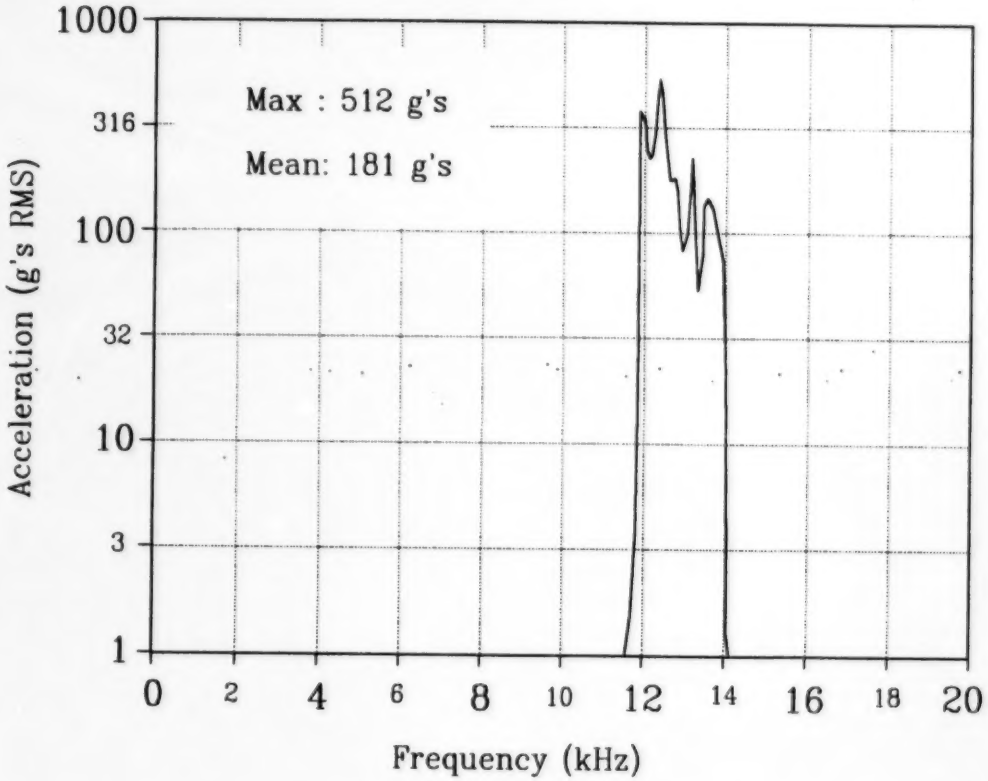
Test No 21 - Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 12.0 – 14.0 kHz. Duration: 22 hrs.

Drive Input: 1.0 V Date: October 11/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 3.0 mm

Percent unattached: Test 90%
Control 28%

Figure A–22

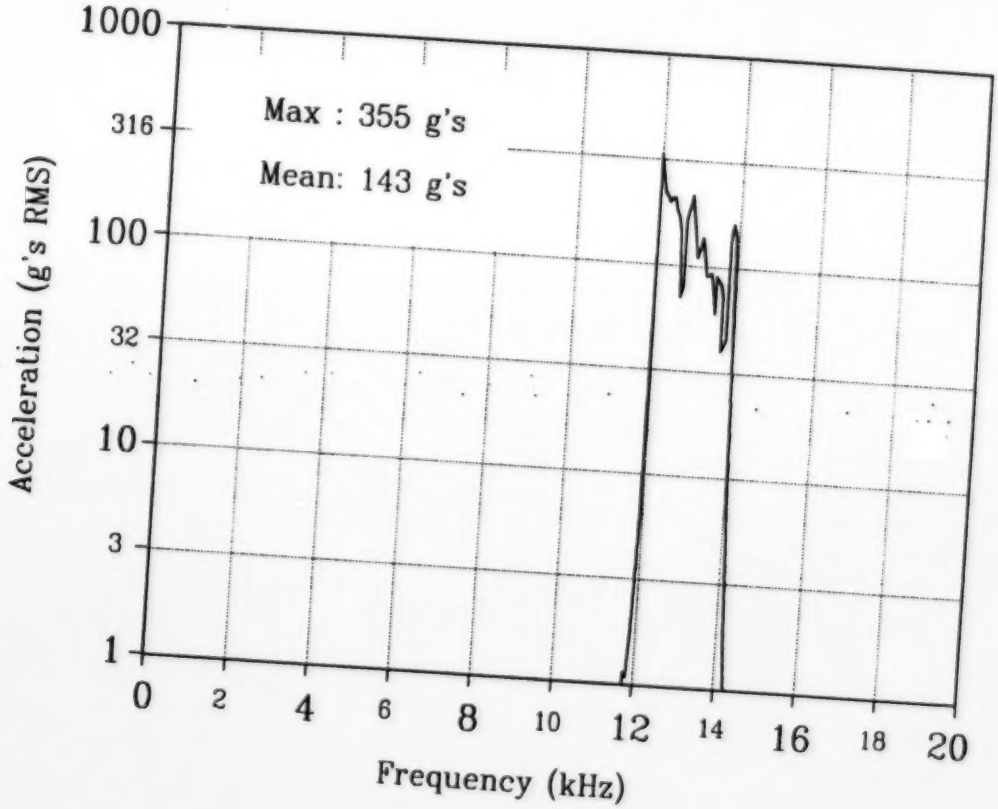
Test No 22 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 12.0 – 14.0 kHz. Duration: 2 hrs.

Drive Input: 1.0 V Date: October 15/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 – 3.0 mm

Percent unattached: Test 90%

Control 20%

Figure A–23

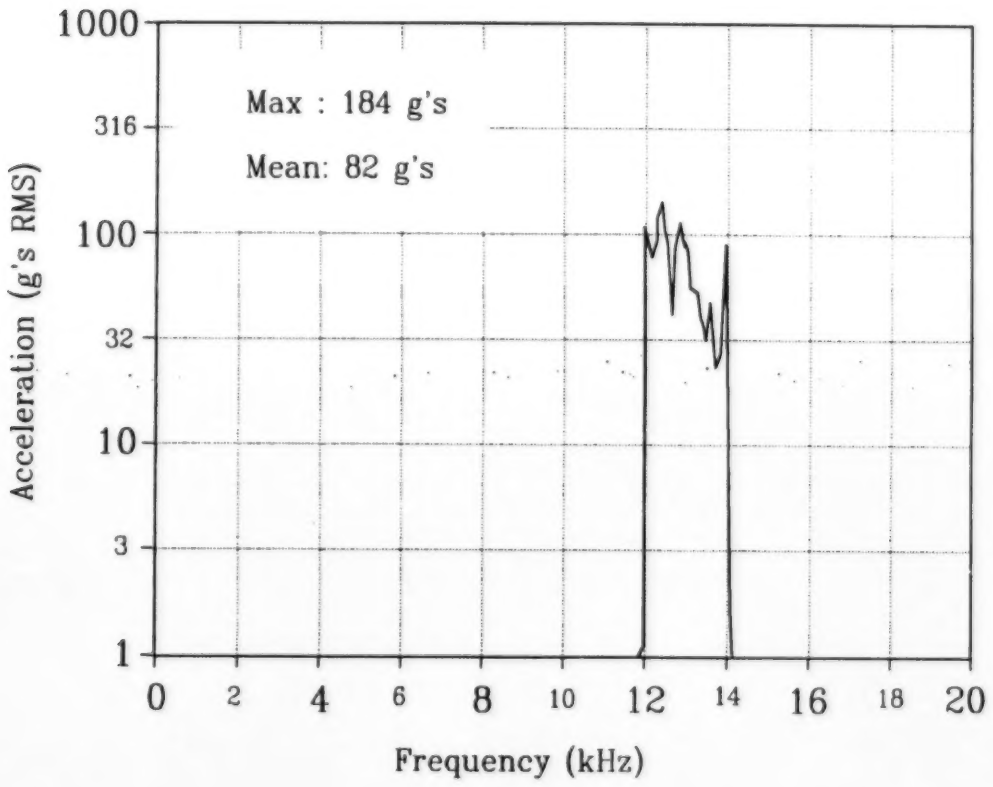
Test No 23 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 12.0 – 14.0 kHz. Duration: 18 hrs.

Drive Input: 1.0 V Date: October 15/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 – 3.0 mm

Percent unattached: Test 50%
Control 18%

Figure A-24

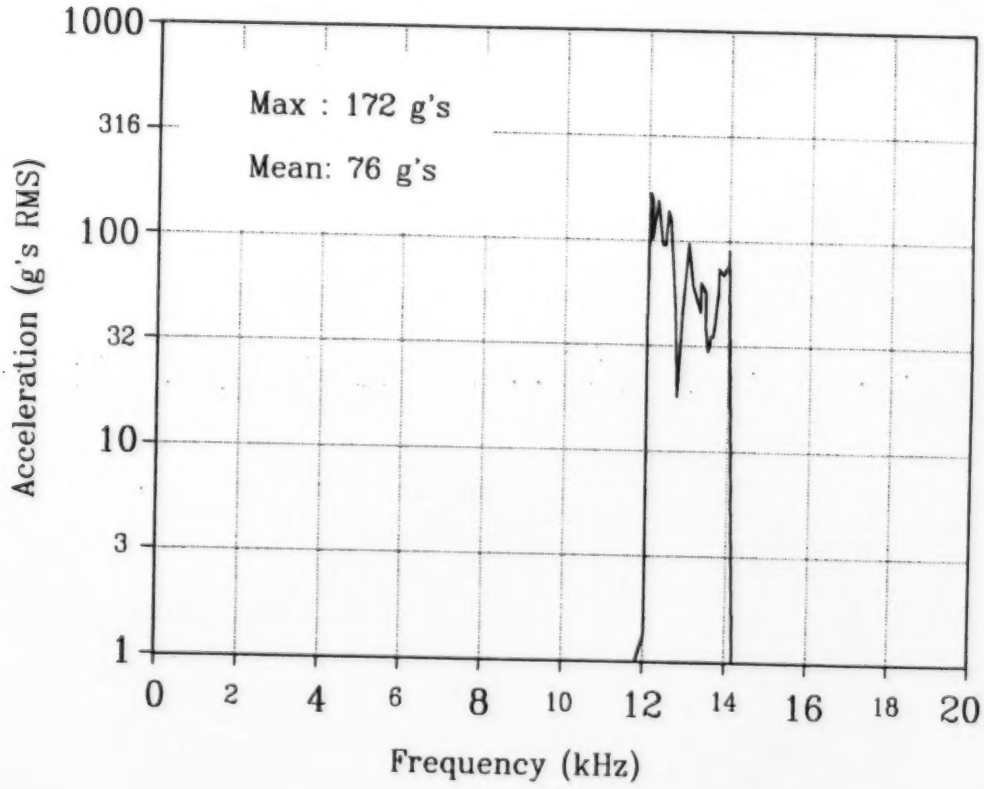
Test No 24 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: C (see Figure 7)

Frequency Range: 12.0 – 14.0 kHz. Duration: 5 hrs.

Drive Input: 0.5 V Date: October 18/90

Sweep Rate: 10 seconds



Mussel Size: 2.0 – 4.0 mm

Percent unattached: Test 62%

Control 22%

Figure A–25

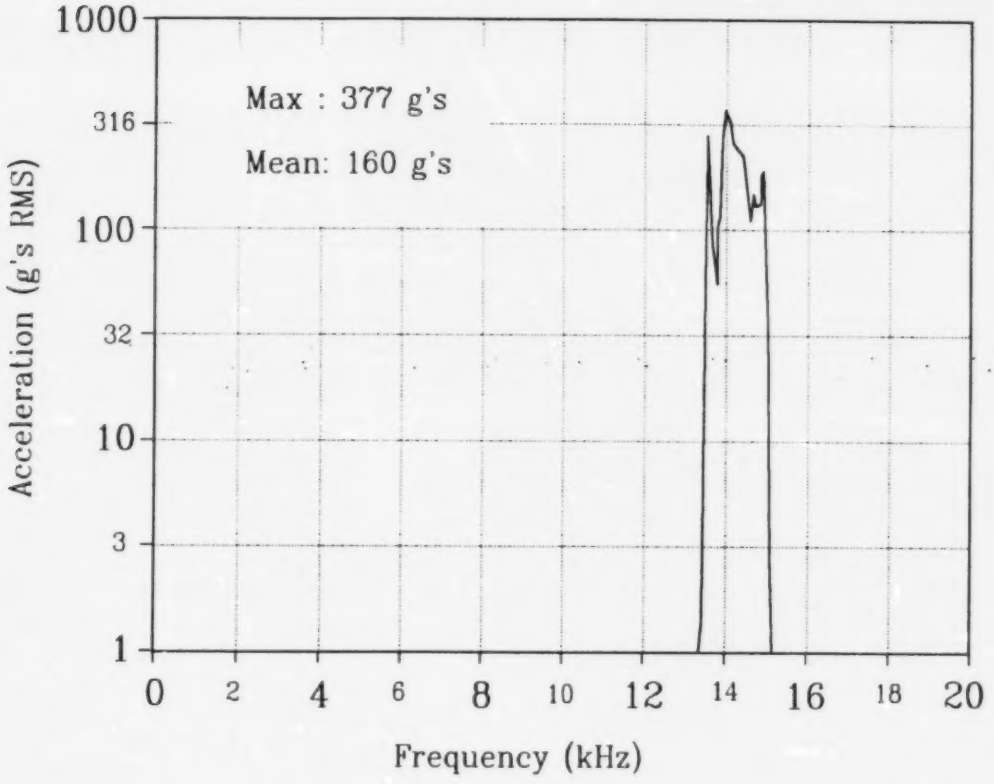
Test No 25 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 13.5 – 15.0 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: September 6/90

Sweep Rate: 10 seconds



Mussel Size: 1.0 – 3.0 mm

Percent unattached: Test 90%
Control 46%

Figure A–26

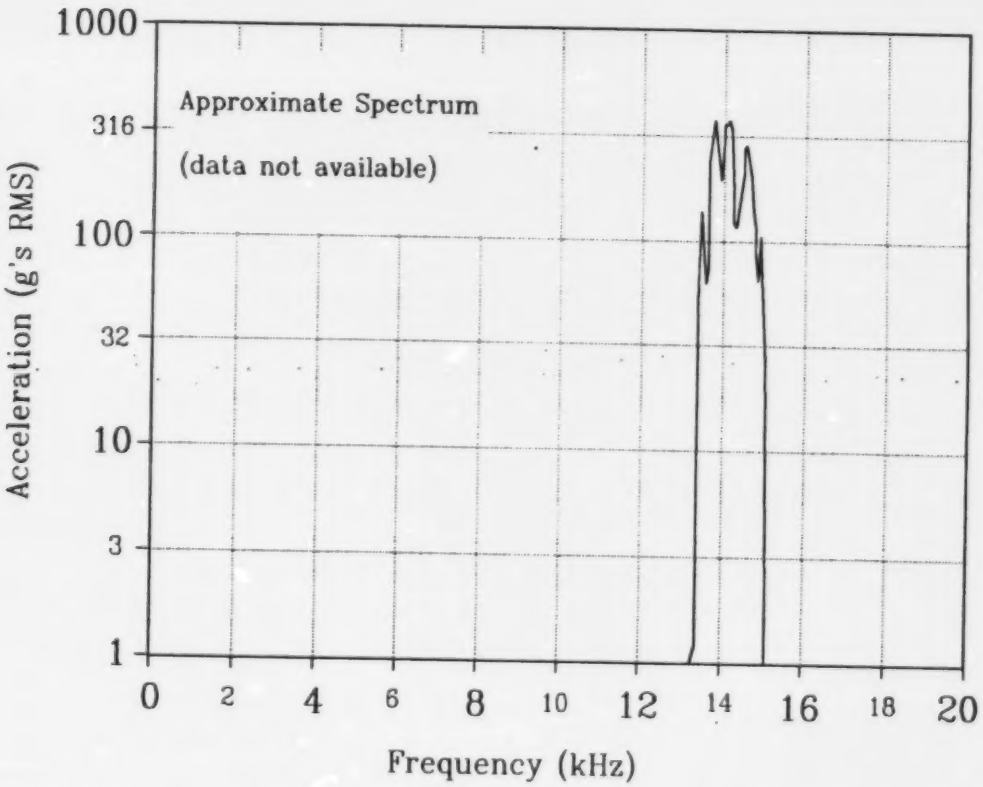
Test No 26 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: B (see Figure 6)

Frequency Range: 13.5 – 15.0 kHz. Duration: 19 hrs.

Drive Input: 1.0 V Date: October 9/90

Sweep Rate: 10 seconds



Mussel Size: 0.5 – 2.0 mm

Percent unattached: Test 90%

Control 16%

Figure A–27

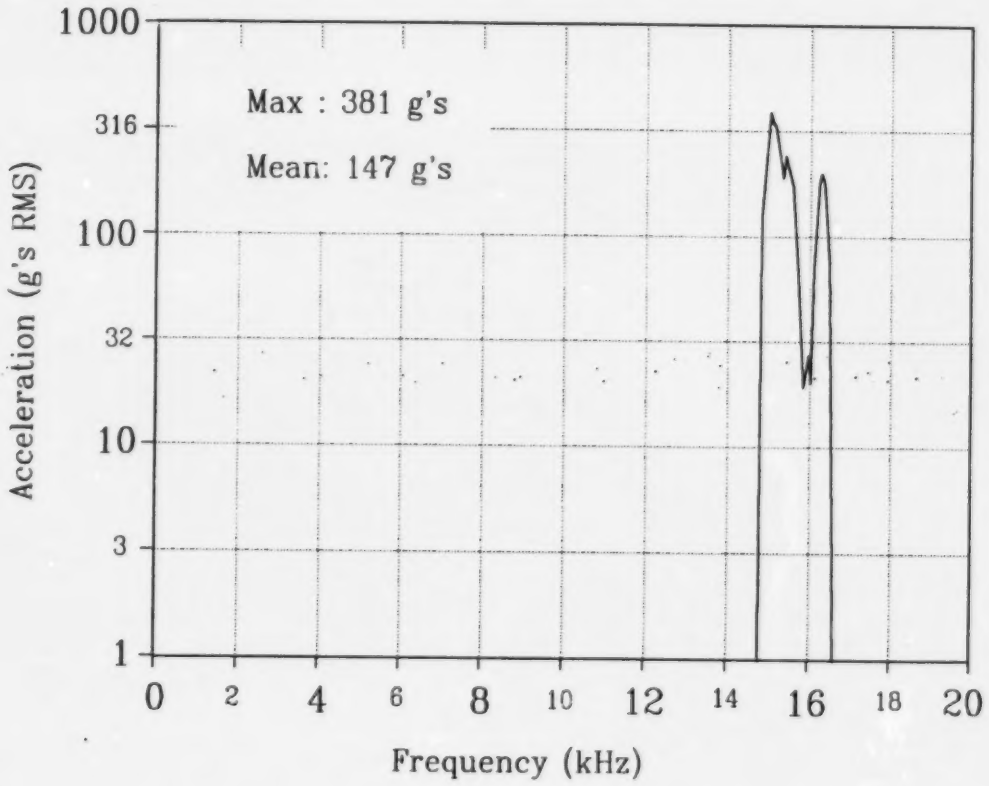
Test No 27 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 15.0 – 16.5 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: September 11/90

Sweep Rate: 10 seconds



Mussel Size: < 1.0 mm

Percent unattached: Test 50%
Control 12%

Figure A–28

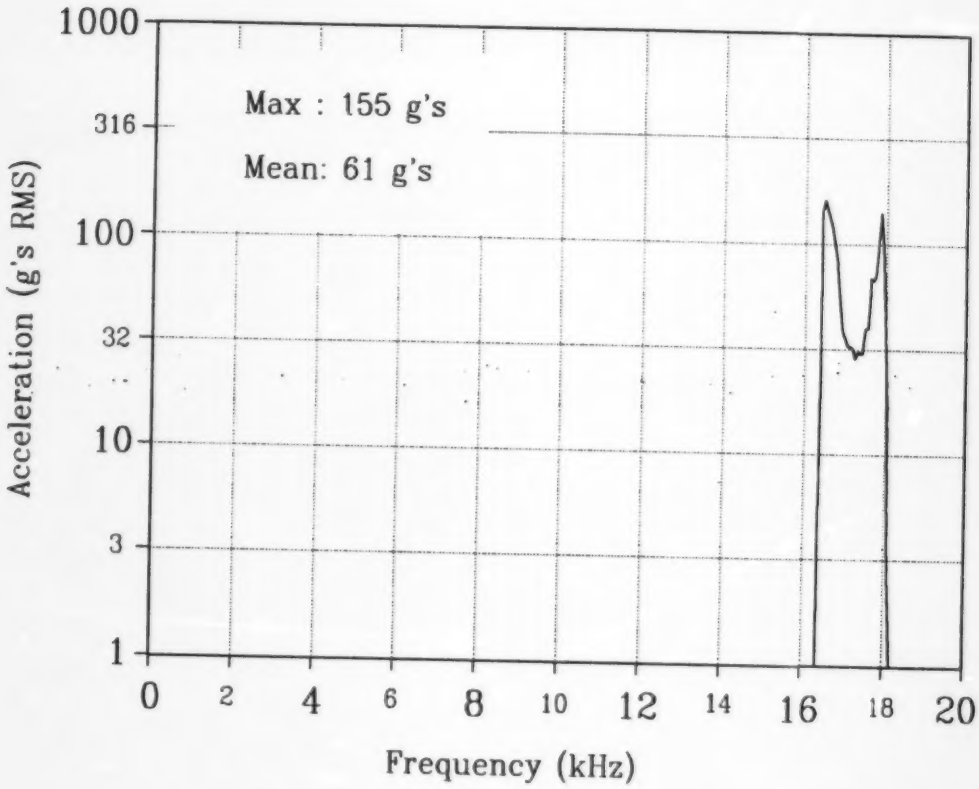
Test No 28 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

Test Arrangement: A (see Figure 5)

Frequency Range: 16.5 – 18.0 kHz. Duration: 24 hrs.

Drive Input: 1.0 V Date: September 12/90

Sweep Rate: 10 seconds



Mussel Size: < 1.0 mm

Percent unattached: Test 12%
Control 9%

Figure A–29

Test No 29 – Acoustical Experiments for Controlling Zebra Mussels Attachment.

APPENDIX B

Statistical Analysis comparing the number of unattached and mortality as a function of amplitude and frequency

APPENDIX B - RAW DATA USED IN STATISTICAL ANALYSIS

FREQUENCY RANGE 1 (8 - 10, 9 - 10.5)

AMPLITUDE	C1 UNATT	EX UNATT	C1 MORT	EXP. MORT
30	24	15	0	4
74	12	90	1	88
119	19	92	2	79
153	13	85	4	81
158	2	58	2	58

FREQUENCY RANGE 2 (10 - 12, 10.5 - 12)

AMPLITUDE	C1 UNATT	EX UNATT	C1 MORT	EXP.MORT
52	13	38	0	24
141	10	43	0	35
201	38	100	4	100
211	16	104	1	104
257	14	100	1	100
263	19	67	1	25
292	29	100	2	100
347	17	100	1	100

FREQUENCY RANGE 3 (12 - 13.5, 12 - 14)

AMPLITUDE	C1 UNATT	EX UNATT	C1 MORT	EXP.MORT
76	22	60	0	9
82	18	49	1	10
143	21	74	3	33
160	32	42	2	5
181	28	49	1	40
207	5	33	1	33
219	11	65	1	63

APPENDIX C

Raw data showing the number of unattached and mortaility for some specific tests

APPENDIX C - RAW DATA

OBS	FREQ	AMP	TREAT	TOTAL	UNATT	MORT	PERUN	PERMOR
1	8.0	74	1	92	12	1	13.043	8.333
2	8.0	74	2	98	90	88	91.837	97.778
3	8.0	74	3	105	23	2	21.905	8.696
4	8.0	30	1	98	24	0	24.490	0.000
5	8.0	30	2	98	15	4	15.306	26.667
6	8.0	30	3	103	18	2	17.476	11.111
7	9.0	119	1	96	19	2	19.792	10.526
8	9.0	119	2	92	92	79	100.000	85.870
9	9.0	119	3	99	34	6	34.343	17.647
10	9.0	158	1	93	2	2	2.151	100.000
11	9.0	158	2	102	58	58	56.863	100.000
12	9.0	158	3	91	11	6	12.088	54.545
13	9.0	153	1	99	13	4	13.131	30.769
14	9.0	153	2	99	85	81	85.859	95.294
15	9.0	153	3	94	33	8	35.106	24.242
16	10.0	201	1	101	38	4	37.624	10.526
17	10.0	201	2	100	100	100	100.000	100.000
18	10.0	201	3	96	80	18	83.333	22.500
19	10.5	263	1	101	19	1	18.812	5.263
20	10.5	263	2	100	67	25	67.000	37.313
21	10.5	263	3	102	46	5	45.098	10.870
22	10.5	292	1	93	29	2	31.183	6.897
23	10.5	292	2	100	100	100	100.000	100.000
24	10.5	347	1	97	17	1	17.526	5.882
25	10.5	347	2	100	100	100	100.000	100.000
26	10.5	211	1	98	16	1	16.327	6.250
27	10.5	211	2	105	104	104	99.048	100.000
28	10.5	257	1	100	14	1	14.000	7.143
29	10.5	257	2	100	100	100	100.000	100.000
30	10.0	52	1	103	13	0	12.621	0.000
31	10.0	52	2	99	38	24	38.384	63.158
32	10.0	52	3	102	4	1	3.922	25.000
33	10.0	141	1	100	10	0	10.000	0.000
34	10.0	141	2	89	43	35	48.315	81.395
35	10.0	141	3	100	23	8	23.000	34.783
36	12.0	160	1	97	32	2	32.990	6.250
37	12.0	160	2	85	42	5	49.412	11.905
38	12.0	160	3	93	40	2	43.011	5.000
39	12.0	207	1	106	5	1	4.717	20.000
40	12.0	207	2	93	33	30	35.484	90.909
41	12.0	207	3	88	8	2	9.091	25.000
42	12.0	219	1	95	11	1	11.579	9.091
43	12.0	219	2	93	65	63	69.892	96.923
44	12.0	219	3	103	61	20	59.223	32.787
45	12.1	143	1	105	21	3	20.000	14.286
46	12.1	143	2	98	74	33	75.510	44.595
47	12.1	143	3	100	30	2	30.000	6.667
48	12.1	181	1	99	28	1	28.283	3.571
49	12.1	181	2	90	49	40	54.444	81.633
50	12.1	181	3	106	11	0	10.377	0.000
51	12.1	82	1	103	18	1	17.476	5.556
52	12.1	82	2	103	49	10	47.573	20.408
53	12.1	82	3	103	21	3	20.388	14.286
54	12.1	76	1	101	22	0	21.782	0.000
55	12.1	76	2	96	60	9	62.500	15.000
56	12.1	76	3	105	30	1	28.571	3.333

CODE

1. FREQUENCY

   8.0 = 8-10 kHz

   9.0 = 9-10.5 kHz

   10.0 = 10-12 kHz

   10.5 = 10.5 - 12 kHz

   12.0 = 12 - 14 kHz

   12.1 = 12.5 - 14 kHz

2. TREAT

   1 - CONTROL

   2 - EXPERIMENTAL

   3 - "CONTROL" IN EXPERIMENTAL TANK